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Cenozoic stratigraphy and geologic history of southwestern Arizona

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ABSTRACT

Recently obtained seismic data and the results of stratigraphic drilling in southwestern Arizona indicate that several alluvium-covered valleys in this area are underlain by more than 3,000 m of Cenozoic deposits. These deposits, with the exception of the marine late Miocene clastic wedge of the Yuma basin and the Pliocene Bouse Formation of the lower Colorado River valley, are the result of continental sedimentation. For the most part, these continental rocks consist of locally derived clastic sediments and lesser amounts of interbedded volcanic rocks and, in some valleys, thick bodies of evaporites. On the basis of their position in the stratigraphic sequence in relation to regional or semiregional unconformities, the Cenozoic sequence of southwestern Arizona was subdivided into an older Unit I and a younger Unit II. The boundary between these two units is a widespread unconformity surface resulting from an important period of subsidence, block-faulting, and erosion that began in late Miocene time (13 to 12 m.y. ago). The two Cenozoic units have been dated and correlated on the basis of radiometric age determination of the interbedded extrusive volcanic rocks, on lithologic character, and with the help of seismic interpretation.

Sedimentation during early Cenozoic time (Unit I) took place in broad interior depressions under predominantly continental conditions. The late Miocene block-faulting episode changed the geography of southwestern Arizona and gave the area a typical basin-and-range structure of mountain-forming horsts separated by valleys underlain by grabens or half-grabens. The prevailing structural grain trends in a northwest direction. Unit II sediments were deposited in these troughs or grabens during late Cenozoic time. At least two of the five troughs located in the eastern part of the area studied contain thick sequences of evaporites that indicate interior drainage. These evaporites are assigned a late Miocene age on the basis of K-Ar ages for associated extrusive volcanic rocks and by their position in the stratigraphic sequence in relation to the late Miocene block-faulting episode. Exterior drainage systems were developed beginning sometime between 10.5 and 6 m.y. ago and have evolved progressively to give the area its present-day geomorphology.

INTRODUCTION

An exploration program in the Basin and Range province of southwestern Arizona undertaken by Exxon Company, U.S.A. (Fig. 1) has provided new data concerning the area's Cenozoic stratigraphy. Seismic mapping and stratigraphic drilling revealed the presence beneath some valley floors of more than 3,000 m of post-Laramide clastic sedimentary rock, volcanic extrusions, and, in places, anomalously thick bodies of evaporites. Except for two marine wedges

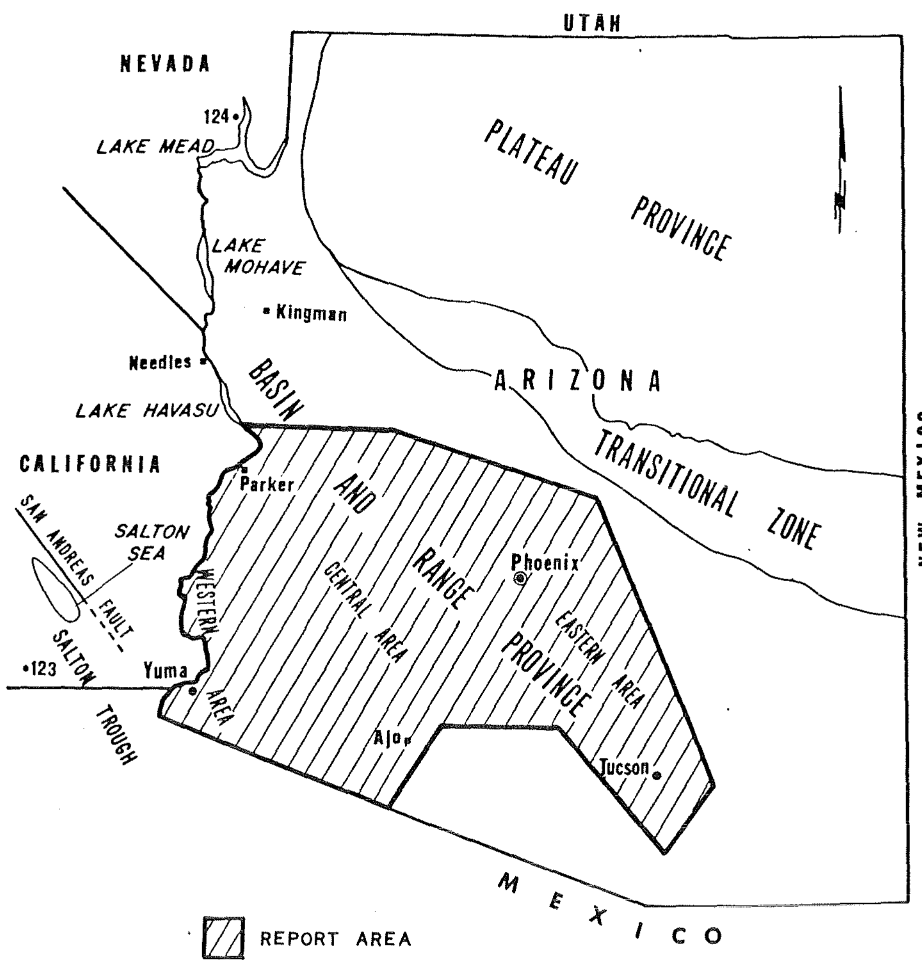

Figure 1. Map showing report area (modified after Wilson and Moore, 1959).

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in the lower Colorado River valley, the rocks studied are products of continental deposition. The Cenozoic section was found to be barren of marker fossils, to contain many abrupt facies changes, and to be faulted to such an extent that reliable regional lithologic correlations could not be made. Correlation was accomplished, however, by using radiometric ages determined from K-Ar ratios in extrusive volcanic intervals interbedded with the sediments. These ages were correlated with a magmatic chronology already in use in Arizona (Damon, 1964; Damon and Mauger, 1966). The correlated ages were then used in combination with geologic and seismic data to subdivide the Cenozoic deposits into two unconformity-bound stratigraphic units (Fig. 2).

Although part of the study was regional, most of the seismic work and all of the drilling were done within a narrow arc extending from Yuma through Phoenix to the vicinity of Tucson (Fig. 3). This report summarizes the study and describes how the findings relate to observations made by others in surrounding regions.

STRATIGRAPHY

Nearly all of the Cenozoic rocks in the studied area are products of nonmarine sedimentation, deposited under oxidizing conditions in fluviatile and lacustrine environments. Included in the sedimentary sequence are some extrusive volcanic rocks. The section is almost devoid of marker fossils. Only a few of the lacustrine clays and tuff beds contain fresh-water ostracods, of which species of *Candona* are the most abundant. *Candona* sp. ranges throughout the Mesozoic and Cenozoic rocks but is most abundant in the upper Cenozoic. In isolated localities, mammalian fossil remains have been recorded (Bryan, 1925; Lance, 1960; McKee and Anderson, 1971). In the study described here, fossils were of little value in dating or correlating the continental Cenozoic rocks.

The only marine rocks occur in the Yuma basin west of the Gila Mountains (Fig. 3) and northward along the lower Colorado River valley. In the Yuma basin, test holes have encountered a marine Miocene section below the Bouse Formation (Mattick and others, 1973). Marine sediments of Bouse age were deposited farther north along the lower Colorado River valley during a Pliocene invasion of the sea (Metzger, 1968).

Cenozoic rocks of southwestern Arizona have been subdivided by previous workers, using such criteria as degree of deformation, association with volcanic rocks, similarity in lithologic composition, correlation with present physiography, and presence or absence of mineralization (Heindl, 1959; Lance, 1960; Cooley and Davidson, 1963; Sell, 1968). Within the last decade, radio-

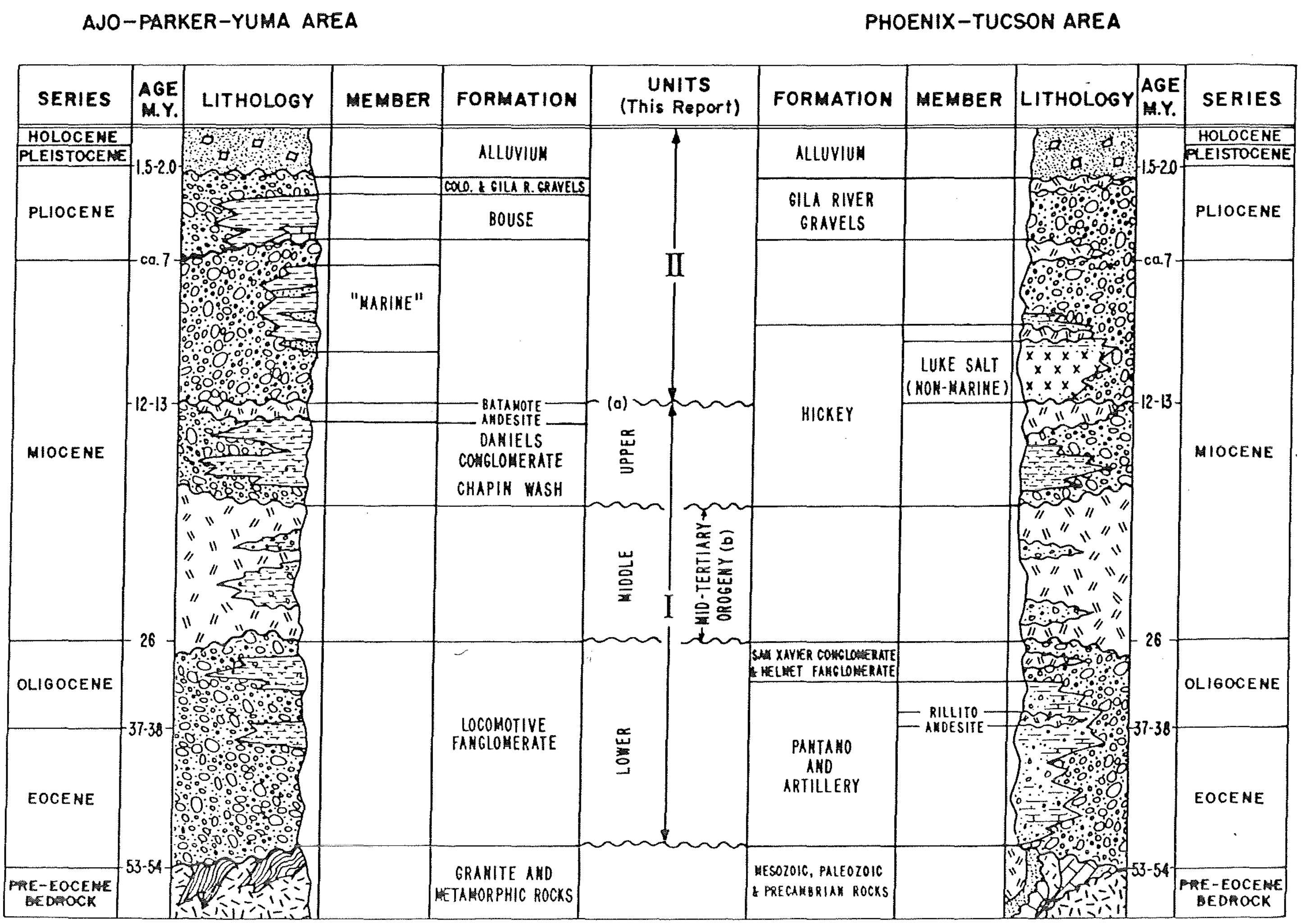

Figure 2. Composite stratigraphic column of southwestern Arizona (ages of series boundaries from Geological Society of London, 1964, p. 260–262). Unconformity (a) represents erosional surface that was disrupted by beginning of late Miocene block faulting. Mid-Tertiary orogeny (b) modified from Damon (1964, p. 13–15). Terminology references: Wilson (1933), Gilluly (1946), Lasky and Webber (1949), Heindl (1959), Cooper (1960), Metzger (1968), Finnell (1970), McKee and Anderson (1971), Eaton and others (1972), and Mattick and others (1973).

metric age determination of igneous rocks has become the most reliable method to establish a time-stratigraphic framework in the continental-volcanic Cenozoic sequence.

During this study, all available data were utilized to establish the Cenozoic stratigraphy of southwestern Arizona. Published surface sections were compiled and 93 outcrop localities were visited. About 29,000 m of well cuttings from 56 oil and gas tests and deep water wells, mostly in Maricopa and Yuma Counties, were studied for lithology and stratigraphic relationships. These initial sample descriptions were supplemented by the study of the cuttings from Exxon's four stratigraphic tests (see Appendix 1). Published radiometric ages of volcanic rocks were augmented with 57 new radiometric age determinations (Tables 1 through 3[1]). In addition, an extensive net of seismic lines was utilized to complete the interpretation of the subsurface stratigraphy.

Results of integrating all this information indicated that the lithologic composition of the Cenozoic section did not lend itself to the ready recognition of distinct lithologic units. Similarly, the lack of time-diagnostic fossils made it impossible to determine reliably the time stratigraphy of the section. The available information indicated, however, that a major unconformity could be recognized within the Cenozoic stratigraphic section throughout southwestern Arizona and that several less important unconformities could also be identified over

[1] Copies of GSA supplementary material 78-4 (Table 2, Analytical Data for K-Ar Ages Determined for This Report, and Table 3, Analytical Data for Rb-Sr Ages Determined for This Report) may be ordered from Documents Secretary, Geological Society of America, 3300 Penrose Place, Boulder, Colorado 80301.

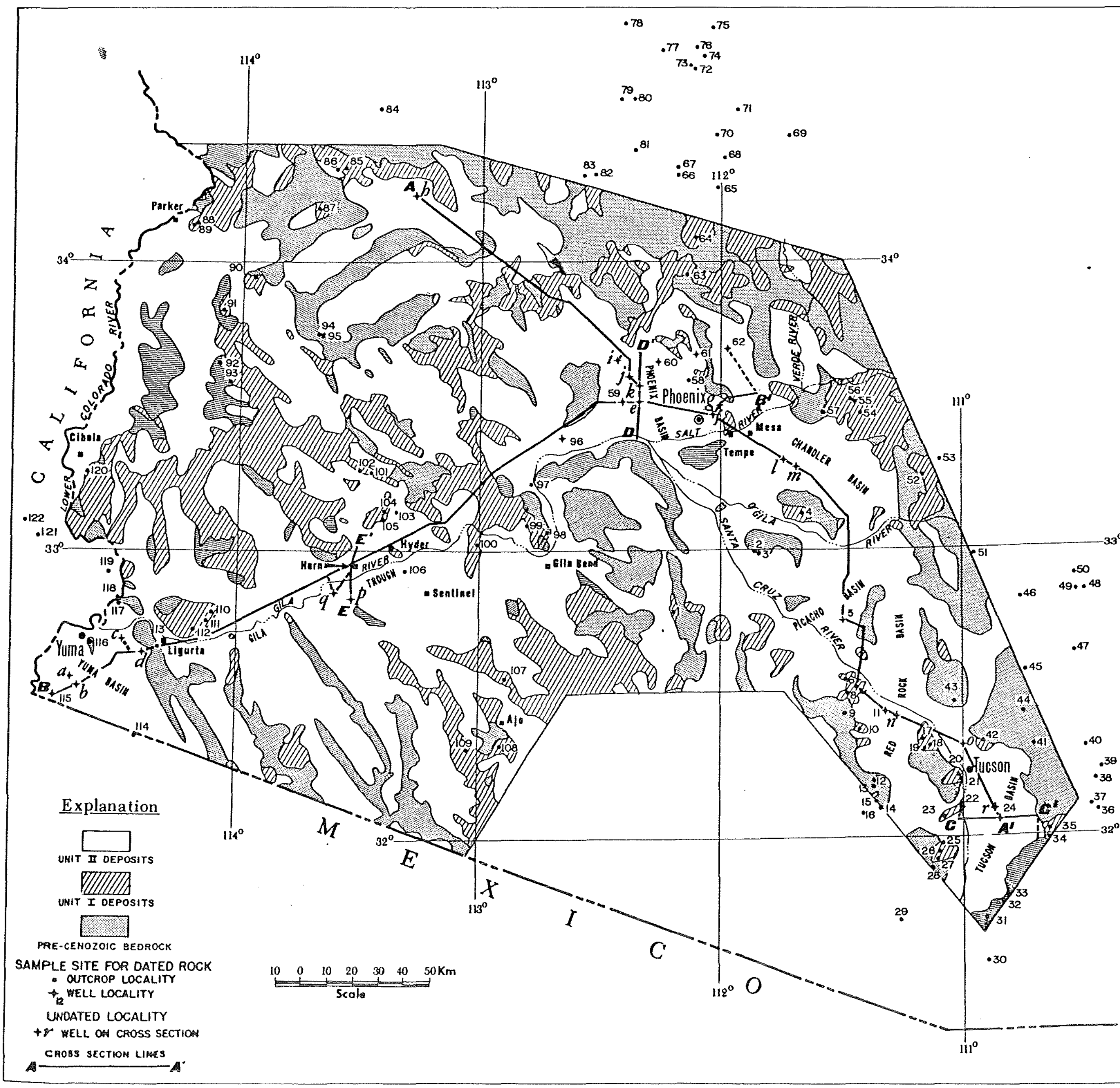

Figure 3. Geologic map of report area (modified from Wilson and others, 1969).

TABLE 1. RADIOMETRIC AGES OF ROCK SAMPLES IN SOUTHWESTERN ARIZONA AND ADJACENT AREAS

Sample locality	Rock type, igneous body, or stratigraphic formation	Location	Apparent age (m.y.)	Radiometric age method, mineral dated	Reference, sample no., comments
1	Basalt (Antelope Peak)	lat 32°47′51″N, long 112°10′30″W	23 ± 5.2	K-Ar, whole rock	This report
2	Granite	lat 32°59′30″N, long 111°51′00″W	861 ± 26 853 ± 26	K-Ar, muscovite	Balla (1972), KA-71-70
3	Monzonite	lat 32°59′00″N, long 111°49′00″W	71.7 ± 2 70.9 ± 2	K-Ar, biotite	Balla (1972), KA-71-69
4	Welded tuff	lat 33°07′32″N, long 111°39′14″W	160 ± 8.0	K-Ar, biotite	This report. Age is spurious; tuff is probably Miocene
5	Exxon State (74) No. 1	NW¼NW¼ sec. 2, T. 8 S., R. 8 E., Pinal County			This report
	2,792–2,807 m (basalt)		17 ± 1.0	K-Ar, whole rock	
	2,823–2,924 m (ultrapotassic trachyte)		14.9 ± 0.3	K-Ar, whole rock	Shafiqullah and others (1976), UAKA 73-140 and 74-87. Average age
	3,101–3,102 m (quartz diorite gneiss)		25 ± 1.4	K-Ar, biotite	K-Ar date of 25 m.y. is reduced age. Rb-Sr date indicates Precambrian age
	3,101–3,102 m (quartz diorite gneiss		1,275 1,540	Rb-Sr, whole rock	
6	Sasco Andesite	Samaniego Hills, Pinal and Pima Counties	15.2 ± 4.8	K-Ar, whole rock	Eastwood (1970), RLE-20-68
7	Cerro Prieta Basalt	Samaniego Hills, Pinal and Pima Counties	17.6 ± 1.3 26.6 ± 0.8	K-Ar, whole rock K-Ar, whole rock	Eastwood (1970), RLE-27-67 Eastwood (1970), RLE-31-68
8	Samaniego Andesite	Samaniego Hills, Pinal and Pima Counties	19.8 ± 1.2	K-Ar, whole rock	Eastwood (1970), RLE-27-68
9	Quartz latite	lat 32°26′36″N, long 111°29′30″W	25.0 ± 2.0	K-Ar, biotite	Mauger and others (1965), RM-4-63
10	Petroglyph Hill Andesite	lat 32°23′07″N, long 111°24′42″W	27.9 ± 1.4	K-Ar, biotite	Damon and Bikerman (1964); Mauger and others (1965), PED-1-63
11	Berry No. 1 Federal 1,057–1,072 m (welded tuff)	NE¼SE¼ sec. 27, T. 11 S., R. 10 E., Pima County	29 ± 2.4	K-Ar, whole rock	This report
12	Basalt dike	lat 32°12′34″N, long 111°22′14″W	9.7 ± 1.7	K-Ar, whole rock	Bikerman (1967), MB-17-64
13	Rhyodacite (Recortado ash flow)	lat 32°10′44″N, long 111°21′24″W	12.6 ± 0.6	K-Ar, sanidine	Bikerman (1967), MB-3-64
14	Basalt	lat 32°05′50″N, long 111°19′17″W	10.4 ± 1.3	K-Ar, whole rock	Bikerman (1967), MB-7-64
15	Basaltic andesite	lat 32°07′29″N, long 111°19′50″W	23.5 ± 1.4	K-Ar, whole rock	Bikerman (1967), MB-12-64
16	Basaltic andesite	lat 32°04′03″N, long 111°24′23″W	23.3 ± 0.7	K-Ar, whole rock	Bikerman (1967), MB-6-64
17	Safford Peak Dacite	lat 32°20′44″N, long 111°08′55″W	24.5 ± 0.9	K-Ar, biotite	Bikerman and Damon (1966), PED-1-64
18	Safford Tuff	lat 32°19′43″N, long 111°08′21″W	25.2 ± 1.4	K-Ar, biotite	Bikerman and Damon (1966), PED-10-63
19	Rillito Andesite	lat 32°19′34″N, long 111°08′22″W	38.5 ± 1.3	K-Ar, biotite	Bikerman and Damon (1966), PED-9-63
20	Uppermost basaltic andesite (Tumamoc Hill)	lat 32°12′47″N, long 111°00′20″W	19.8 ± 3.0	K-Ar, whole rock	Bikerman and Damon (1966), PED-8-63
21	"A" Mountain gray tuff	lat 32°12′32″N, long 110°59′22″W	25.8 ± 0.9 29.7 ± 0.9	K-Ar, sanidine K-Ar, sanidine	Bikerman and Damon (1966), PED-76-63 Bikerman and Damon (1966), PED-17-62
22	Basaltic andesite (Martinez Hill)	Sw¼ sec. 23, T. 15 S., R. 13 E., Pima County	23.5 ± 0.7	K-Ar, whole rock	Percious (1968), JKP-10-67
23	Basaltic andesite (Black Mountain). Overlies San Xavier Conglomerate	sec. 6, T. 16 S., R. 12 E., Pima County	24.8 ± 0.7	K-Ar, whole rock	Percious (1968), JKP-49-66
24	Exxon State (32) No. 1	NE¼NE¼SW¼ sec. 5, T. 16 S., R. 15 E., Pima County			This report
	2,420–2,426 m (andesitic basalt)		23.4 ± 0.6	K-Ar, whole rock	VAKA-72-66
	2,895–2,898 m (andesitic basalt)		16.1 ± 0.6	K-Ar, whole rock	VAKA-72-70. Interpreted to be intrusive body, possibly sill or dike
	2,972–3,002 m (andesitic basalt)		18.0 ± 2.0	K-Ar, whole rock	VAKA-72-70
	3,753 m (quartz monzonite)		61 120 ± 60	K-Ar, whole rock Rb-Sr, whole rock	K-Ar date is reduced date. VAKA-72-78 See localities 28 and 31
25	Andesite	lat 31°56′45″N, long 111°04′15″W	24	K-Ar, biotite	Marvin and others (1973); Creasey and Kistler (1962), 7
26	Turkey track porphyry (pillow lava in Helmet Fanglomerate)	lat 31°57′06″N, long 111°04′30″W	30.7 ± 1.2	K-Ar, plagioclase	Damon (1968), RM-2-64a

27	Fine tuff in Helmet Fanglomerate	lat 31°55′49″N, long 111°06′49″W	27.9 ± 2.6	K-Ar, biotite	Damon and Bikerman (1964), RM-1-64
28	Alkali Granite	lat 31°54′N, long 111°11′30″W	55 ± 3	K-Ar, biotite	Marvin and others (1973); Cooper (1971), T169
			150 ± 20	Pbα, zircon	K-Ar date is reduced age. See locality 31
29	Basaltic andesite	lat 31°43′N, long 111°15′W	23.4 ± 0.9	K-Ar, whole rock	Damon (1969), JKP-2-68
30	Rhyodacite vitrophyre (Grosvenor Hills Volcanics)	lat 31°34′05″N, long 110°53′10″W	26.2 ± 1.9	K-Ar, plagioclase	Marvin and others (1973); Drewes (1971a), 710
31	Elephant Quartz Monzonite	lat 31°43′35″N, long 110°53′50″W	69.0 ± 2.9	K-Ar, biotite	Marvin and others (1973); Drewes (1968, 1971a), 876
			190 ± 30	Pbα, zircon	Drewes (1968), p. C13–C14 suggests that monzonite is recrystallized Squaw Gulch Granite of Jurassic age
32	Rhyolite vitrophyre (Box Canyon dike swarm)	lat 31°45′30″N, long 110°48′05″W	25.9 ± 1.3	K-Ar, sanidine	Marvin and others (1973); Drewes (1971b), 899
33	Continental Granodiorite	lat 31°47′55″N, long 110°48′30″W	55.5 ± 2.4	K-Ar, biotite	Marvin and others (1973); Drewes (1971b), 1046
			1,360 ± 200	Pbα, zircon	K-Ar date is reduced age. Biotite shows recrystallization fabric
34	Rhyolite ash flow (Pantano Formation)	lat 31°59′48″N, long 110°38′36″W	36.7 ± 1.7	K-Ar, sanidine	Damon and Bikerman (1964), PED-13-62
			32.8 ± 2.6	K-Ar, biotite	
35	Pantano tuff	lat 32°01′24″N, long 110°38′06″W	29.2 ± 0.9	K-Ar, biotite	Damon (1966), PED-7-65
	Turkey-track porphyry (upper part of Pantano Formation)	Location unknown	24.4 ± 2.6	K-Ar, biotite	Finnell (1970)
36	Quartz monzonite	lat 32°06′N, long 110°26′W	1,540 ± 60	K-Ar, biotite	Marvin and others (1973)
37	Quartz monzonite	lat 32°07′N, long 110°28′W	23.5 ± 0.9	K-Ar, biotite	Marvin and others (1973)
			24.8 ± 0.9	K-Ar, muscovite	
38	Granodiorite	lat 32°12′N, long 110°27′W	27.3 ± 1.1	K-Ar, biotite	Marvin and others (1973)
			36.8 ± 1.6	K-Ar, muscovite	
39	Mica schist (Pinal Schist)	lat 32°13′30″N, long 110°25′30″W	33.8 ± 1.2	K-Ar, biotite	Marvin and others (1973); recrystallized Precambrian. Pinal Schist
			29.0 ± 0.9	K-Ar, muscovite	
40	Turkey-track porphyry (overlies Mineta Formation)	lat 32°20′15″N, long 110°29′50″W	26.3 ± 2.4	K-Ar, plagioclase	Damon (1970), PED-3-69
41	Banded gneiss	lat 32°20′03″N, long 110°41′04″W			Livingston and others (1967), Mauger and others (1968), PED-18-62L
	light band		25.4 ± 1.0	K-Ar, muscovite	
			25.1 ± 1.0	K-Ar, biotite	
			26.8 ± 0.8	K-Ar, orthoclase	
	dark band		27.5 ± 0.9	K-Ar, biotite	PED-18-62d
42	Banded gneiss	lat 32°20′06″N, long 110°55′04″W	31.2 ± 0.9	K-Ar, muscovite	Mauger and others (1968), PED-56-66
43	Quartz monzonite gneiss	lat 32°28′N, long 111°05′W	27.3 ± 0.9	K-Ar, biotite	Mauger and others (1968), PED-20-62
44	Leatherwood Quartz Diorite	lat 32°26′N, long 110°45′W	29.6 ± 0.6	K-Ar, biotite	Damon (1969), PED-1-68
45	Quartz monzonite	lat 32°35′N, long 110°45′W	1,420	K-Ar, plagioclase	Livingston and others (1967), DEL-13-62
			1,370	K-Ar, biotite	
46	Rhyolite dike	lat 32°50′00″N, long 110°45′30″W	22.3 ± 0.7	K-Ar, biotite	Krieger (1973b)
47	Vitric tuff in Quiburis Formation	lat 32°39′10″N, long 110°32′52″W	4.6 ± 0.4	K-Ar, glass	Damon (1969), LDA-1-66
48	Tuff	lat 32°51′30″N, long 111°29′54″W	24.4 ± 1	K-Ar, biotite	Krieger (1968b)
49	Quartz latite	lat 32°51′34″N, long 110°32′06″W	25.6	K-Ar, biotite	Krieger (1968b)
			25.4	K-Ar, sanidine	Krieger (1968b)
50	Rhyolite tuff	lat 32°54′52″N, long 110°32′48″W	24.6 ± 1	K-Ar, biotite	Krieger (1968a)
			22.4 ± 1	K-Ar, sanidine	
51	Rhyolite tuff	lat 32°58′45″N, long 110°56′45″W	24.1 ± 0.7	K-Ar, sanidine	Krieger (1973a)
52	Quartz latite (uppermost formation on Picketpost Mountain)	lat 33°15′20″N, long 111°09′21″W	18.0 ± 0.5	K-Ar, biotite	Damon (1966), PED-11-65
			18.2 ± 2.5	K-Ar, plagioclase	
53	Superior Dacite (ash flow overlying Whitetail Conglomerate)	lat 33°18′36″N, long 111°05′00″W	19.9 ± 0.9	K-Ar, biotite	Damon (1966), PED-4-62
54	Welded tuff	lat 33°28′36″N, long 111°25′41″W	22.6 ± 1.0	K-Ar, biotite	Damon (1969), PED-18-68
55	Dacite dome	lat 33°31′11″N, long 111°27′25″W	20.1 ± 1.2	K-Ar, biotite	Damon (1969), PED-16-68
56	Basalt	lat 33°31′26″N, long 111°28′02″W	17.8 ± 3.1	K-Ar, whole rock	Damon (1969), PED-14-68

TABLE 1. *(Continued)*

Sample locality	Rock type, igneous body, or stratigraphic formation	Location	Apparent age (m.y.)	Radiometric age method, mineral dated	Reference, sample no., comments
57	Quartz latite lava	lat 33°28′21″N, long 111°34′45″W	21.3 ± 0.8	K-Ar, biotite	Damon (1969), PED-17-68
58	John Jacobs Probe No. 2 380–382 m (basalt)	NW¼SW¼SW¼ sec. 23, T. 3 N., R. 2 E., Maricopa County	20 ± 2.6	K-Ar, whole rock	This report
59	Goodyear Farms water well 469–487 m (basalt)	NE¼SW¼SE¼ sec. 14, T. 2 N., R. 1 W., Maricopa County	10.5 ± 4.5	K-Ar, whole rock	This report. Basalt overlies thick halite found in Arizona Salt Co. and El Paso Natural Gas Co. well in sec. 2, T. 2 N., R. 1 W.
60	G. D. Isabel no. 1, Maricopa County	NW¼SW¼SW¼ sec. 27, T. 4 N., R. 1 E., Maricopa County			This report. K-Ar date of 51 m.y. appears spurious. Lower basalt is probably upper Oligocene or lower Miocene
	288–325 m (basalt		23 ± 7.7	K-Ar, whole rock	
	586–610 m (basalt)		51 ± 3.3	K-Ar, biotite	
61	Sperry Gyroscope No. 1	NW¼NW¼NW¼ sec. 19, T. 4 N., R. 3 E., Maricopa County			This report. K-Ar date of 44 m.y. appears spurious. Basaltic andesite is probably upper Oligocene or lower Miocene.
	222–271 m (basalt)		22 ± 1.9	K-Ar, biotite	
	466–472 m (basaltic andesite)		44 ± 5	K-Ar, biotite	
62	Biery #1 Federal 1,430–1,442 m (basaltic andesite)	SE¼SE¼SW¼ sec. 8, T. 4 N., R. 4 E., Maricopa County	22 ± 1.2	K-Ar, whole rock	This report
63	Basalt (underlies white tuff and clastics)	lat 33°58′10″N, long 112°07′36″W	20 ± 1.3	K-Ar, whole rock	This report
64	Basalt (overlies white tuff and clastics)	lat 34°04′20″N, long 112°06′30″W	15 ± 2.1	K-Ar, whole rock	This report, probably Hickey Formation
65	Basalt (Hickey Formation)	lat 34°16′42″N, long 112°02′22″W	10.4 ± 0.4	K-Ar, whole rock	McKee and Anderson (1971), MY6
66	Basalt (Hickey Formation)	lat 34°18′21″N, long 112°11′09″W	13.1 ± 0.5	K-Ar, whole rock	McKee and Anderson (1971), MY5
67	Latite protusive dome	lat 34°21′00″N, long 112°11′30″W	18.5 ± 0.6	K-Ar, hornblende	McKee and Anderson (1971), MY1
68	Basalt (Hickey Formation)	lat 34°22′51″N, long 112°00′18″W	11.0 ± 0.5	K-Ar, whole rock	McKee and Anderson (1971), MY7
69	Hackberry Mountain Tuff (Hickey Formation)	27 km east of locality 70	14 ± 7	K-Ar, biotite	Damon (1964), BES-58-282
70	Basalt (Hickey Formation)	lat 34°27′27″N, long 112°02′51″W	10.1 ± 0.4	K-Ar, whole rock	McKee and Anderson (1971), MY8
71	Black Hills Basalt	lat 34°32′07″N, long 111°56′14″W	12.8 ± 2.2	K-Ar, whole rock	Damon (1968), PED-28-66
72	Basalt (Hickey Formation)	lat 34°41′57″N, long 112°07′15″W	11.6 ± 0.5	K-Ar, whole rock	McKee and Anderson (1971), MM2
73	Mingus Mountain Basalt	lat 34°42′10″N, long 112°08′21″W	12.9 ± 0.8	K-Ar, whole rock	Damon (1968), PED-9-67
74	Trachyandesite flow (Hickey Formation)	lat 34°44′29″N, long 112°06′25″W	14.6 ± 1.1	K-Ar, biotite	Krieger and others (1971), MM4
75	Basalt (Verde Formation)	lat 34°49′42″N, long 112°02′45″W	4.5 ± 0.2	K-Ar, whole rock	McKee and Anderson (1971), CD2
76	Basalt (Hickey Formation)	lat 34°45′20″N, long 112°07′03″W	14.0 ± 0.6	K-Ar, whole rock	McKee and Anderson (1971), CD1
77	Sullivan Buttes Latite	lat 34°45′23″N, long 112°15′28″W	23.4 ± 1.0	K-Ar, biotite	Krieger and others (1971), PA5
78	Sullivan Buttes Latite	lat 34°51′08″N, long 112°25′19″W	26.7 ± 1.1	K-Ar, hornblende	Krieger and others (1971), PA4
79	Basalt (Hickey Formation)	lat 34°34′44″N, long 112°26′21″W	13.1 ± 0.5	K-Ar, whole rock	McKee and Anderson (1971), PR3
80	Basalt (Hickey Formation)	lat 34°34′45″N, long 112°22′30″W	13.4 ± 0.5	K-Ar, whole rock	McKee and Anderson (1971), PR2
81	Basalt (Hickey Formation)	lat 34°23′36″N, long 112°21′45″W	13.5 ± 0.5	K-Ar, whole rock	McKee and Anderson (1971), MU2
82	Latite flow (Milk Creek Formation)	lat 34°18′57″N, long 112°31′48″W	14.8 ± 0.5	K-Ar, biotite	McKee and Anderson (1971), K2
83	Latite flow (Milk Creek Formation)	lat 34°18′24″N, long 112°34′45″W	14.6 ± 0.5	K-Ar, biotite	McKee and Anderson (1971), K3
84	Basalt	Along Hwy. 93, NW¼ sec. 20, T. 14 N., R. 11 W., Mohave County	22	K-Ar, whole rock	This report
85	Basalt (upper part of Artillery Formation)	lat 34°19′55″N, long 113°35′34″W	21 ± 3.6	K-Ar, whole rock	This report; Lasky and Webber (1949)
86	Cobwebb Basalt	lat 34°19′17″N, long 113°36′12″W	13 ± 2.1	K-Ar, whole rock	This report; Lasky and Webber (1949)

87	Crystal tuff (intercalated with lake beds)	lat 34°11′28″N, long 113°41′16″W	48 ± 2.8	K-Ar, biotite	This report. Age appears spurious Tuff is probably upper Oligocene or lower Miocene
88	Basalt	lat 34°07′12″N, long 114°13′17″W	16.4 ± 0.7 15.1 ± 4.4	K-Ar, whole rock K-Ar, whole rock	Damon (1970), PED-7-68
89	Basalt	lat 34°07′18″N, long 114°13′05″W	20 ± 3.1	K-Ar, whole rock	This report
90	Andesite	lat 33°56′37″N, long 113°55′31″W	21 ± 1.2	K-Ar, biotite	This report
91	Welded rhyolitic tuff	lat 33°49′52″N, long 114°05′38″W	24 ± 1.6	K-Ar, biotite	This report
92	Quartz monzonite	Plomosa Mountains	1,730 1,750	Pbα, zircon	Miller and McKee (1971)
93	Rhyodacite	lat 33°35′10″N, long 114°02′35″W	19.1 ± 0.6 20.2 ± 0.6	K-Ar, hornblende K-Ar, biotite	Miller and McKee (1971)
94	Granodiorite	lat 33°44′46″N, long 113°40′27″W	69	K-Ar, biotite	This report
95	Granodiorite	lat 33°45′00″N, long 113°40′31″W	65.0 ± 5.5	K-Ar, biotite	Damon (1968), PED-3-68
96	Reeves No. 1 Fuqua 1,050–1,062 m (basalt)	NE¼NW¼ sec. 34, T. 1 N., R. 4 W., Maricopa County	72 ± 13.2	K-Ar, biotite	This report. Age appears spurious. Basalt probably Miocene
97	Basalt	lat 33°13′50″N, long 112°46′28″W	6 ± 1.8	K-Ar, whole rock	This report
98	Gneissic granite	lat 33°03′10″N, long 112°42′50″W	984 ± 39.0	K-Ar, biotite	This report
99	Welded rhyolite tuff (upper part of Sil Murk Formation)	lat 33°04′52″N, long 112°47′48″W	27 ± 3.8	K-Ar, whole rock	This report
100	Basalt	lat 33°01′03″N, long 112°59′58″W	18 ± 7.2	K-Ar, whole rock	This report
101	Rhyolitic tuff (intercalated with sediments underlying lacustrine limestone	lat 33°16′23″N, long 113°26′51″W	23 ± 1.6	K-Ar, biotite	This report
102	Basaltic andesite	lat 33°16′43″N, long 113°29′41″W	28 ± 4.2	K-Ar, biotite	This report
103	Exxon State (14)-1	NW¼SE¼ sec. 25, T. 3 S., R. 11 W., Yuma County			This report
	299–238 m (andesite)		20.5 ± 1.0	K-Ar, whole rock	VAKA-72-54
	771–777 m (gneissic granite)		163.7 ± 4.0 1,080	K-Ar, whole rock Rb-Sr, whole rock	VAKA-72-57. K-Ar date of 163.7 m.y. is reduced age. Gneissic granite recrystallized in Jurassic time
	799 m (aphanitic volcanic rock)		21.3 ± 0.9	K-Ar, whole rock	VAKA-72-58. Highly brecciated and veined with calcite. Interpreted to be fissure dike.
104	Leucocratic rhyolite	lat 33°08′11″N, long 113°23′52″W	18.5 ± 1.5	K-Ar, whole rock	This report, VAKA-72-48
105	Basalt	lat 33°06′59″N, long 113°33′51″W	29.3 ± 3.1	K-Ar, whole rock	This report, VAKA-72-47
106	Basalt	lat 32°56′06″N, long 113°18′05″W	3.0 ± 0.9	K-Ar, whole rock	This report
107	Basalt	lat 32°33′03″N, long 112°52′43″W	21 ± 1.2	K-Ar, whole rock	This report
108	Basalt (Ajo Volcanics). Overlies Locomotive Fanglomerate	lat 32°19′37″N, long 112°52′13″W	25 ± 2.7	K-Ar, whole rock	This report
109	Basalt (Batamote Andesite); overlies Daniels Conglomerate	lat 32°18′20″N, long 113°00′26″W	15 ± 2.2	K-Ar, whole rock	This report
110	Rhyolitic tuff intercalated with red clastics	lat 32°47′17″N, long 114°06′19″W	23 ± 2.7	K-Ar, whole rock	This report
111	Muggins Mountain Tuff	lat 32°45′17″N, long 114°07′54″W	21.9 ± 0.9	K-Ar, biotite	Damon (1968), PED-23-67
112	White crystal tuff intercalated with poorly consolidated clastics	lat 32°42′41″N, long 114°11′36″W	78 ± 4.3	K-Ar, biotite	This report. Age is spurious. Some biotite is metamorphic and actual age is probably Miocene
113	Gneiss	lat 32°39′46″N, long 114°18′58″W lat 32°39′33″N, long 114°19′17″W	319 ± 15.7 198 ± 9.4	K-Ar, biotite K-Ar, biotite	This report. Gneiss is interpreted as Precambrian. Reduced age represents Mesozoic recrystallization, probably during Jurassic time
114	Los Cerritos Gneiss	38 km southeast of San Luis, Sonora, Mexico	58 ± 3.1 57 ± 3.3	K-Ar, biotite	This report. Gneiss is probable Precambrian. Reduced age probably represents Laramide recrystallization
115	Exxon Yuma-Federal No. 1	SW¼NE¼ sec. 8, T. 11 S., R. 24 W., Yuma County			This report
	2,194–2,224 m (andesitic tuff)		16 ± 31.9	K-Ar, whole rock	
	3,078–3,108 m (andesitic basalt)		20 ± 10	K-Ar, whole rock	Interpreted to be intrusive, possibly sill or dike

TABLE 1. *(Continued)*

Sample locality	Rock type, igneous body, or stratigraphic formation	Location	Apparent age (m.y.)	Radiometric age method, mineral dated	Reference, sample no., comments
116	Granitic gneiss	lat 32°40′16″N, long 114°35′52″W			This report. See comments for locality 114
	fine grained		38 ± 2.0	K-Ar, biotite	
	coarse grained		59 ± 3.2	K-Ar, biotite	
117	Crystal vitric tuff, top of 61-m section of volcanic rocks overlying basement complex; tuff is overlain by fanglomerate	lat 32°48′53″N, long 114°31′40″W	26.3 ± 1.6	K-Ar, biotite	Damon (1966), PED-4-65
118	Basaltic andesite	lat 32°49′58″N, long 114°31′39″W	25.1 ± 1.6	K-Ar, whole rock	Damon (1970), PED-9-68
119	Hornblende andesite	lat 32°56′56″N, long 114°33′12″W	24.7 ± 2.1	K-Ar, hornblende	Damon (1968), PED-1-67
120	Welded rhyolitic tuff	lat 33°15′05″N, long 114°37′38″W	25 ± 1.7	K-Ar, whole rock	This report
121	Basalt	lat 33°03′32″N, long 114°49′55″W	9 ± 1.8	K-Ar, whole rock	This report
122	Vitric tuff in basal limestone of Bouse Formation	lat 33°06′29″N, long 114°52′22″W	5.4	K-Ar, glass	P.E. Damon (1972, oral commun.), PED-4-69
123	Alverson Volcanics (overlain by basal conglomerate of Imperial Formation)	lat 32°47′54″N, long 116°01′34″W, Fossil Canyon, Imperial County, Calif.	16 ± 1.0	K-Ar, whole rock	This report
124	Basalt in upper Muddy Creek Formation (locally domed by underlying salt movement)	lat 36°24′53″N, long 114°24′25″W, Clark County, Nev.	8	K-Ar, whole rock	This report

Note: Sample localities 1 through 122 are shown in Figure 3; localities 123 and 124 are shown in Figure 1.

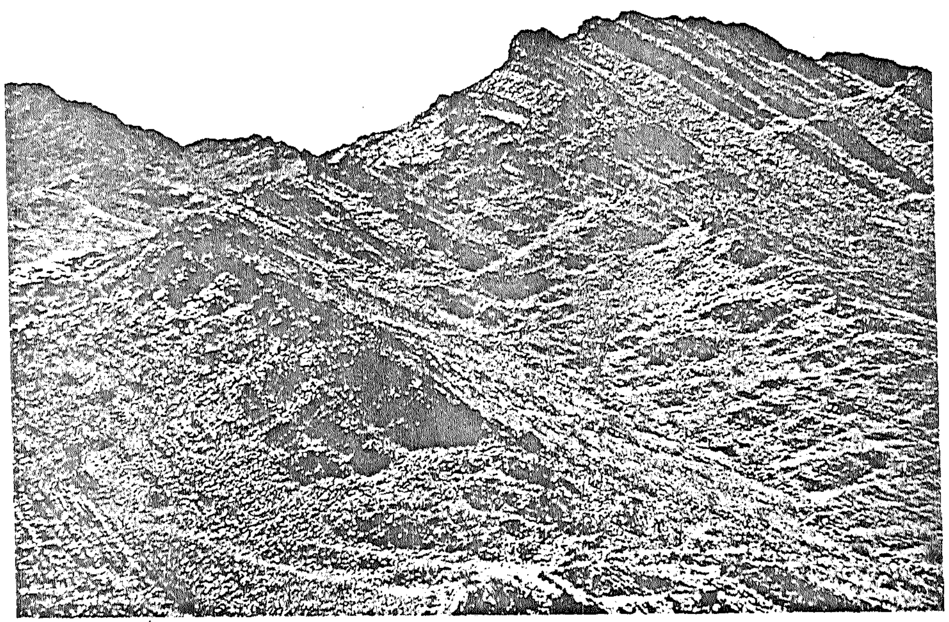

Figure 4. Steep westerly dipping beds of Unit I at northern end of Mohawk Mountains, east of Yuma.

Figure 5. Typical boulder fanglomerate of Unit I.

large parts of the area. It became evident that the most effective way to subdivide the Cenozoic section was by selecting stratigraphic units, not by means of distinctive lithologic characteristics, or chronology determined by fossil evidence, but by their position in the stratigraphic sequence in relation to the unconformity surfaces.

On this basis, the Cenozoic section in southwestern Arizona has been divided into two main unconformity-bounded units (Fig. 2): an older Unit I (Eocene to late Miocene in age), and a younger Unit II (late Miocene to Holocene in age). The boundary between these two units is a widespread, easily recognized unconformity surface resulting from a period of subsidence, block faulting, and erosion, which, on the basis of K-Ar analyses, has been dated as forming between 13 and 12 m.y. ago and somewhat less than 10.5 m.y. ago. It will be referred to as the "late Miocene block-faulting episode."

Unit I rests directly on a major unconformity separating rocks of Eocene to Miocene age from a variety of pre-Eocene rocks ranging in age from Precambrian to Paleocene. Unit I has been locally subdivided into "lower," "middle," and "upper" subunits, also on the basis of readily recognizable unconformity surfaces (Fig. 2). The middle subunit is composed predominantly of volcanic rocks and lesser amounts of interbedded pyroclastic sediments, formed during a period of uplift and volcanism that Damon (1964) has called the "mid-Tertiary orogeny." During this tectonic episode, Lower and Middle Unit I sediments were folded, faulted, intruded by magmas, and eroded.

Figure 2 summarizes the generalized stratigraphic subdivision of the Cenozoic section of southwestern Arizona, suggested as a result of this study. It also shows the relationship of the proposed new units to the local lithologic units previously used by various authors in the area.

Unit I

Unit I (Fig. 4) rests on a floor composed of rocks having a wide range of ages. In the central part of the study area, this "pre-Eocene bedrock" is a crystalline complex of Precambrian granitic and gneissic rocks overlain by Paleozoic rocks in rare cases of preservation. Toward the northwest and southeast, the Paleozoic section is more widespread, thickens, and is overlain by Mesozoic and early Cenozoic (Paleocene) rocks that were subjected to Laramide diastrophism.

Unit I includes all rocks deposited between the beginning of post-Laramide alluviation, about 53 m.y. ago (early Eocene), and the time of the first significant movements of the late Miocene block-faulting episode, about 13 to 12 m.y. ago. Deposition of Unit I occurred in depocenters that were greatly modified during tectonic adjustments and volcanism associated with the mid-Tertiary orogeny.

Rocks of Unit I can be divided into three subunits: (1) a lower subunit that was deposited during the magmatic quiescent period between the Laramide orogeny and the mid-Tertiary orogeny; (2) a middle subunit of volcanic rocks and intercalated sediments deposited during the period of volcanic activity associated with the mid-Tertiary orogeny (about 28 to 17 m.y. ago); and (3) an upper subunit of extrusive volcanic rocks and interbedded sediments separated from older rocks by a profound angular unconformity. This unconformity represents the terminal event of the mid-Tertiary orogeny (Damon and others, 1973).

Lower Unit I. Rocks of the oldest part of Unit I occur as isolated remnants of fluviatile reddish-brown arkosic sandstones and interbedded fanglomerates. In places, the thickness of these rocks is as much as several hundred metres. The sandstones are poorly sorted, moderately to well indurated, and composed of quartz, feldspar, biotite, and fragments of gneissic and granitic rocks. Weathered iron oxides and a reddish-brown silty matrix give a distinctive reddish cast to these sedimentary rocks. The fanglomerates are composed mainly of rounded to subangular cobbles and boulders of gneiss and granite (Fig. 5). Both the sandstones and fanglomerates apparently have been derived from nearby source areas that were parts of a widespread and fairly homogeneous Precambrian gneissic and granitic terrain.

In the northwestern and southeastern parts of the study area, Lower Unit I fluviatile sandstones and conglomerates interfinger with lake beds. These lacustrine sediments locally contain thin algal limestones similar to those found in the Flagstaff Formation of central Utah (Spieker, 1946). Best development of this type of limestone occurs in the Artillery Formation in the Rawhide and Artillery Mountains east of Parker (Fig. 3, loc. 85) where it contains snail shells, *Chara* fruits, and silicified palm roots of Eocene age (Lasky and Webber, 1949).

Lower Unit I ranges in age from Eocene to late Oligocene (53 to about 28 to 26 m.y.) and includes some of the earliest middle Tertiary volcanic extrusions. Two of these are the Rillito Andesite and a bed of ashflow tuff in the Pantano Formation located in the Tucson area. These volcanic rocks have been dated as 38.5 and 36.7 m.y. old, respectively (Table 1, locs. 19, 34). They are approximately contemporaneous with volcanic activity that started in the Mogollon-Datil volcanic province of New Mexico and Arizona as early as 38 m.y. ago (Elston and others, 1973), and in central Nevada about 37 m.y. ago (McKee and Silberman, 1970). Data collected elsewhere in the study area indicate that volcanism was widespread near the end of Oligocene and the beginning of Miocene time (26 m.y. ago).

Middle Unit I (Predominantly Volcanic Rocks). The lower boundary of the middle subunit of Unit I is marked by the beginning of widespread volcanism associated with the mid-Tertiary orogeny. This volcanic episode modified the geometry of earlier depositional basins and produced great quantities of rhyolitic to andesitic tuffs, breccias, and flows. Sediments intercalated with the volcanic rocks consist of indurated torrential deposits of red sand and gravel and massive beds of fanglomerate. Isolated thin beds of algal limestone and mudstone and associated beds of water-laid tuff indicate intermittent local development of lakes. Unconformities are common within the unit.

As indicated by the Middle Unit I rocks, volcanic activity became intense near the end of Oligocene time, spreading during the early Miocene throughout southwestern Arizona and lasting some 6 to 9 m.y. Of the 64 K-Ar–derived ages in Table 1 that fall between 28 and 17 m.y., 50 are in the time interval from 26 to 20 m.y. Twenty of these 64 determinations were made for this study and represent widespread coverage in the study area. They confirm the findings of Damon (1964) and Damon and Mauger (1966), who originally documented the mid-Tertiary magmatic pulse in the Basin and Range province.

Upper Unit I. The middle Miocene continental deposits of Upper Unit I consist of grayish-brown, poorly consolidated sandstones, fanglomerates (containing abundant volcanic detritus), varicolored mudstones, and beds of water-laid tuff. Locally, these sedimentary deposits are intercalated with and overlain by basaltic lava flows. The tuffs are usually cream to white — less commonly, varicolored. Well-preserved fresh-water ostracods are common in the mudstone and tuff beds. Typical of these middle Miocene sedimentary deposits are the Daniels Conglomerate in the Ajo area (Gilluly, 1946) and the Chapin Wash Formation in the Rawhide and Artillery Mountains (Lasky and Webber, 1949).

Along the lower Colorado River valley, in the Parker-Cibola area, a cemented sand and gravel fanglomerate (Metzger, 1968) appears to be time equivalent to the Chapin Wash Formation and Daniels Conglomerate. Some 10 km east of Parker, in Osborne Wash, this fanglomerate rests unconformably on steeply tilted red beds of Unit I (Fig. 6). A K-Ar age of 16.4 m.y. was obtained for a basaltic andesite (Table 1, loc. 88) that can be correlated with other basaltic andesites intercalated in this fanglomerate (P. E. Damon, 1977, written commun.).

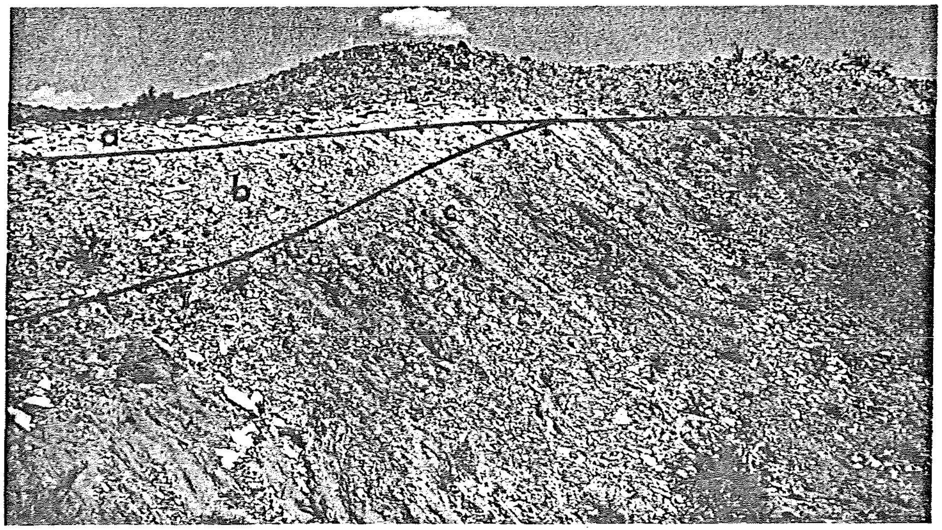

Figure 6. White Bouse limestone (a) of Unit II and gentle westerly dipping middle Miocene fanglomerate (b) of Unit I unconformably overlying tilted red sandstone (c) of Unit I, Osborne Wash east of Parker.

Upper Unit I deposition began as the mid-Tertiary orogeny started to wane about 20 to 17 m.y. ago (locally slightly later). Topographic lows and areas of local subsidence became new sites of alluvial-fan and playa formation.

Unit II

Late Miocene block faulting destroyed previous drainage and depositional patterns and created a new horst-and-graben terrain. The first significant movements of this block faulting occurred after deposition of the Cobwebb Basalt (13 m.y. K-Ar age; Table 1, loc. 86) and other middle Miocene deposits assigned to Upper Unit I that are exposed in the mountain ranges. Rocks of Unit I were faulted and eroded and have a distinct unconformable relationship with the overlying beds of Unit II (Figs. 7, 8). The subsiding fault troughs, or grabens, became depocenters for clastic material eroded from adjacent highlands and, to a lesser ex-

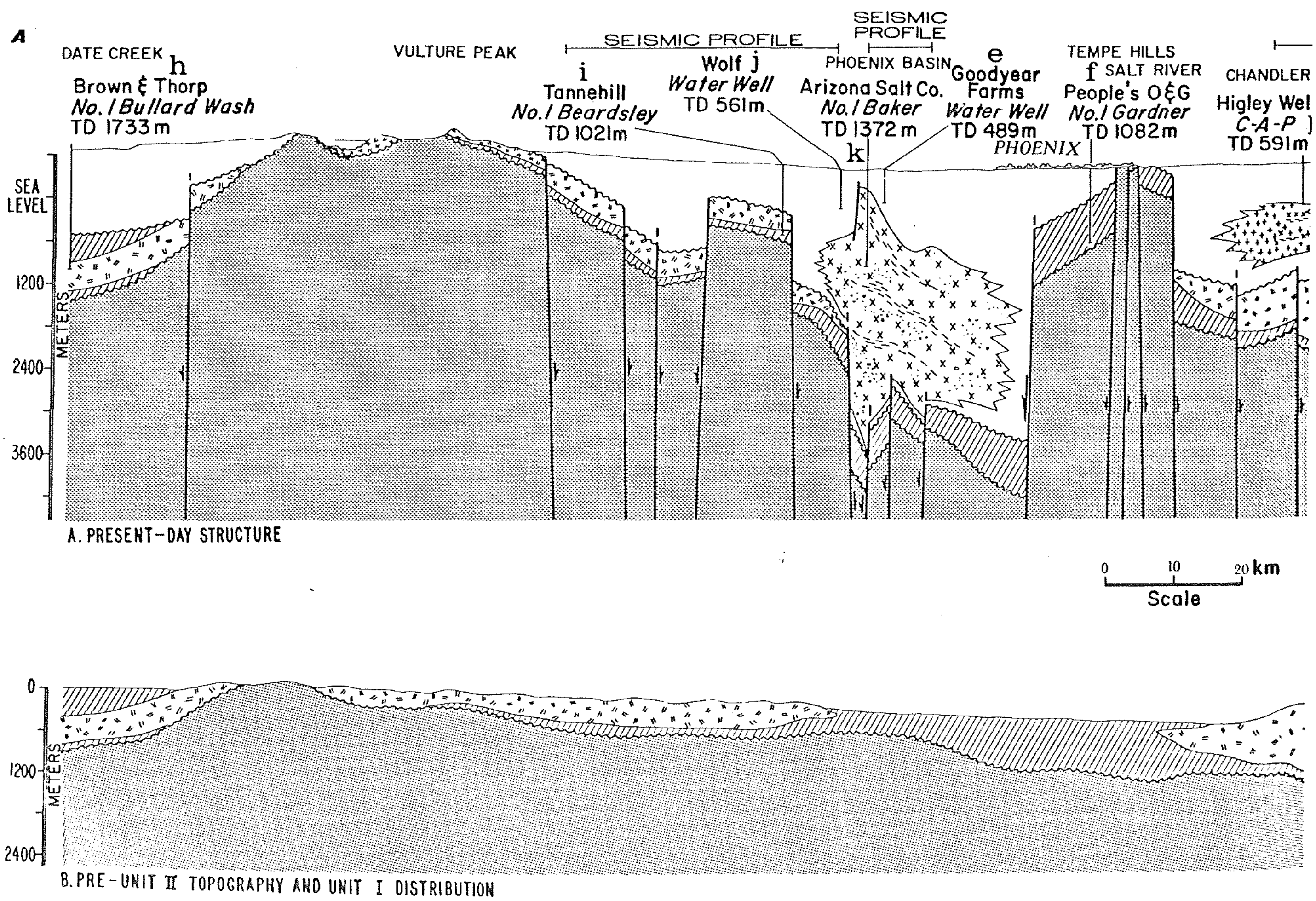

Figure 7. Cross section A–A′ (letters and numbers refer to localities in Fig. 3). Seismic control shown above cross section.

tent, for the products of declining volcanism. Unit II includes the rocks deposited in these grabens.

Unit II can best be described by treating separately three geographic areas in which the sedimentary strata of this unit have distinct and differing characteristics (Fig. 1): (1) an eastern area, where thick fluviolacustrine sediments, containing locally thick bodies of evaporites, accumulated in late Miocene time in rapidly subsiding troughlike basins; (2) a central area, where a much thinner fluviolacustrine sequence, without evaporites, was deposited; and (3) a western area, the Yuma basin and the lower Colorado River valley, where marine sedimentation dominated.

Unit II in Eastern Area. In two of the five troughlike basins that occur between Phoenix and Tucson (Fig. 7), Unit II contains thick evaporite sequences. A well drilled near Phoenix in 1969 by the Arizona Salt Company penetrated 1,219 m of massive halite without reaching its base. This occurrence was described and named the Luke Salt by Eaton and others (1972). Their analysis of halite samples from the Arizona Salt Company well indicated that the bromine content was well below the threshold value indicative of marine halite. On the basis of low bromine content and other data, Eaton and others (1972) concluded that the Luke Salt is probably of nonmarine origin and was probably deposited in a saline lake. The low bromine content was confirmed by Exxon's analysis and substantiates Eaton and others' conclusion. Subsequent seismic mapping by Exxon showed that the Arizona Salt Company drilled into a shallow, large, domelike salt mass possibly more than 3,000 m thick (Fig. 9). The material underlying this salt mass has not been penetrated by wells, but its age and lithology can be postulated from widespread well data and seismic correlations.

The Exxon State (74)-1 well (Appendix 1), located 115 km to the southeast of Phoenix in the Picacho basin, penetrated slightly more than 1,800 m of massive anhydrite containing only minor interbeds of shale, tuff, halite, and limestone nodules. The anhydrite was encountered in a stratigraphic position comparable to that of the Luke Salt, suggesting that at least the upper part of the two evaporite sequences may be time correlative. The State (74)-1 encountered an ultrapotassic trachyte flow at a depth of 2,765 m that yielded a K-Ar age of 14.9 m.y. (middle Miocene; Table 1, loc. 5). Overlying the flow are fanglomerates that grade upward into the Picacho basin evaporites. This evaporite section grades upward into an undated section of red-brown claystone containing some sand, anhydrite, and gypsum. In the Phoenix basin, however, some thin basalt flows are locally intercalated in an equivalent clastic section that lies stratigraphically above the Luke Salt. One of these flows, encountered at 469 m in the Goodyear Farms water well (Table 1, loc. 59), yielded a K-Ar age of 10.5 m.y. (late Miocene). This is approximately the age of younger basalts of the Hickey Formation of central Arizona (McKee and Anderson, 1971). If it is assumed that the Luke Salt and the Picacho basin anhydrite are approximately time equivalent, the occurrence of basalt of late Miocene age in beds above the former and ultrapotassic trachyte of middle Miocene age below the latter dates both evaporites.

Anhydrite and gypsum have been encountered in the Chandler, Red Rock, and

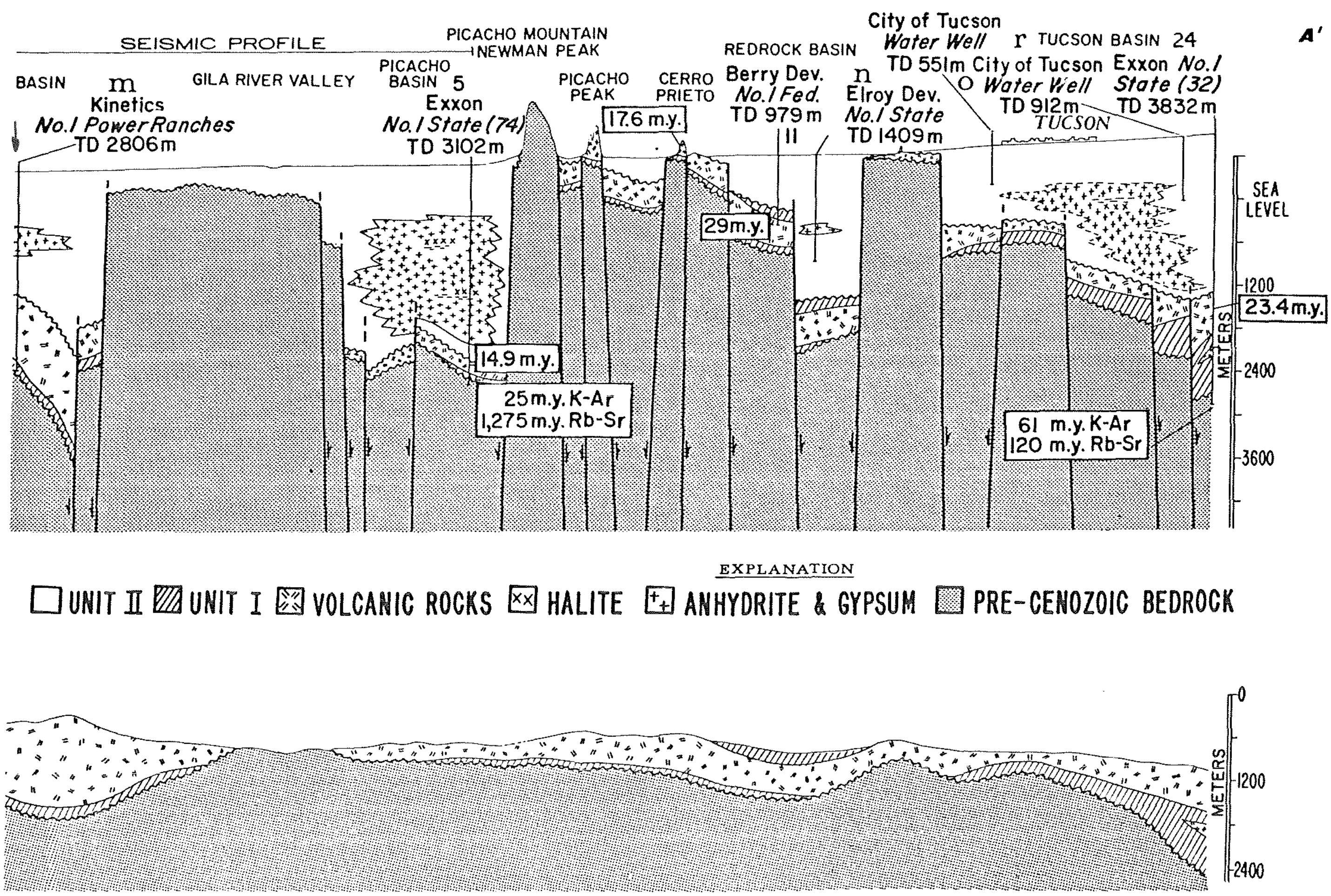

Figure 7. *(Continued).*

Tucson basins, but no thick evaporite sections have been penetrated by wells. These are areas of very sparse deep subsurface control, however, and contain large volumes of unexplored sediments.

More than 1,200 m of relatively pure halite was penetrated in a well north of Kingman in the Hualapai Valley (Peirce, 1972). Peirce believed that this deposit, which he named the Red Lake Salt, is tabular in shape and was formed in a closed basin. The Muddy Creek Formation in the Lake Mead area also contains thick salt deposits (Longwell, 1963). This salt has not been dated, but late Miocene ages have been determined for the overlying Fortification Basalt Member of the Muddy Creek Formation (Anderson and others, 1972).

A sample of a thin basalt flow in the Muddy Creek Formation collected on the west shore of the Overton arm of Lake Mead (Fig. 1) yielded a late Miocene K-Ar age of 8 m.y. (Table 1, loc. 124). Locally, this basalt has been domed by upward movement of the underlying salt. Other basalt flows and dikes that have been assigned to the Fortification Member have yielded K-Ar ages as young as 4.5 m.y (Anderson and others, 1972).

Unit II in Central Area. The central part of the report area lacks the deep Tertiary troughs that characterize the eastern part, and it is probably barren of evaporites. Information from wells drilled by others and from Exxon's seismic data indicates that Unit II in this area is thin and composed of fanglomerates, red-brown clays, and basalt flows. Ross (1923) noted a persistent occurrence of red-brown clay in the subsurface of the lower Gila River area and correlated it with similar deposits in the Mesa area, 20 km east of Phoenix (Lee, 1905). Red-brown clays were also described in the Gila Bend area by Heindl and Armstrong (1963). In the Exxon State (74)-1 well, red-brown clay was encountered between 198 and 707 m directly above the Picacho anhydrite. In the Tucson basin, the same kind of clay was encountered by Exxon's State (32)-1 well (Appendix 1) between 350 and 813 m. In the latter well the interval from 564 to 686 m contained an abundance of gypsum crystals.

Ross concluded that the red-brown clays found in the subsurface of the lower Gila River area were probably lake deposits, and data gathered in this study support that conclusion. Also, these data suggest that the clays were products of the same period of interior drainage that produced the evaporites in the eastern troughs. These red-brown clays grade upward into river-gravel deposits, indicating termination of lacustrine conditions and the development of exterior-drainage systems. Termination of lacustrine conditions occurred between 10.5 and 6.0 m.y. ago, on the basis of the age of basalt overlying the Luke Salt and a

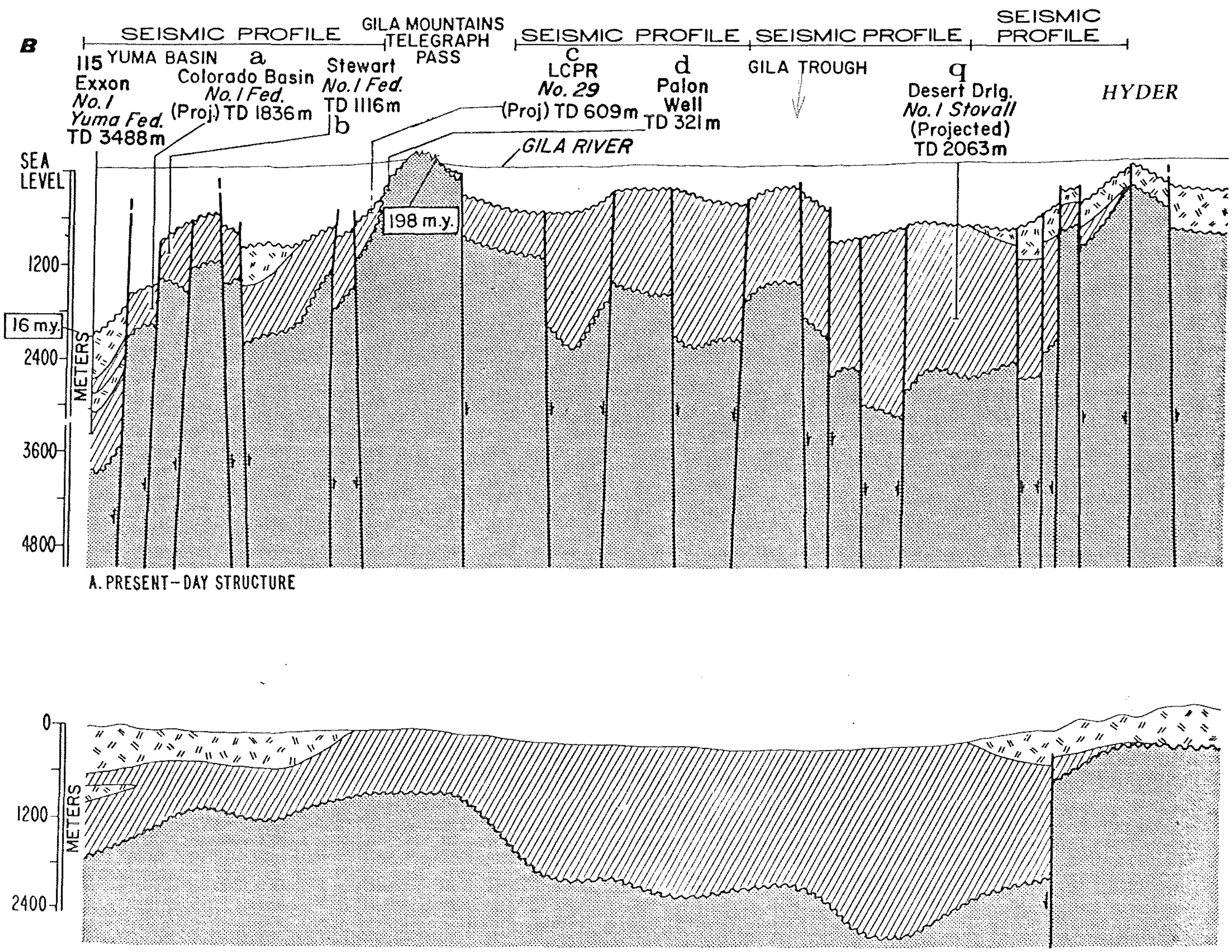

Figure 8. Cross section B–B′ (letters and numbers refer to localities in Fig. 3). Seismic control shown above cross section.

K-Ar age of 6.0 m.y. obtained for a basalt flow overlying minor amounts of river gravels near Gillespie Dam, about 70 km west-southwest of Phoenix (Fig. 3, loc. 97).

Unit II in Western Area. Unit II in the western area consists of a marine wedge of clastic sediments of probable late Miocene age confined to the Yuma basin and the overlying more widespread Pliocene Bouse Formation. Overlying the Bouse Formation are Colorado River gravel deposits.

Marine Upper Miocene Strata of Yuma Basin. In the subsurface of the Yuma basin, a few wells have encountered a marine sequence (Mattick and others, 1973). Exxon's Yuma Federal No. 1 well (Appendix 1), located 25 km southwest of Yuma (Fig. 3, loc. 115), penetrated, from 1,627 to 2,115 m, 488 m of light gray, greenish-gray, and salmon mudstones and fine-grained tuffaceous sandstones. In the basal 40 m, the fine-grained sediments grade downward into a medium- to coarse-grained conglomeratic sandstone that rests unconformably on volcanic rocks and intercalated continental-type sediments. A similar-appearing clastic section was noted between 1,136 and 1,962 m in the Colorado Basin Associates, Inc. Federal No. 1 well, located 10 km northeast of the Exxon well.

Sample cuttings from the Exxon well contain abundant specimens of minute shallow-water foraminifera, scattered pelecypod fragments, and echinoid spines. This fauna, however, was not recognized in the Colorado Basin Associates, Inc. well. Foraminifera observed in cuttings from the Exxon well include abundant benthonic forms of *Bolivina* sp., *Cibicides* sp., and *Nonion* sp. Species of *Discorbis, Spiroplectammina, Gyroidina,* and *Sphaeroidinella* are present in the basal 10 m of the clastic sequence. No specific determination of these forms was possible and, consequently, they could not be used for age determinations.

A late Miocene age is assigned to this marine clastic sequence on the basis of the following relationships: (1) the beds are overlain unconformably by the Pliocene Bouse Formation; (2) dipmeter data from the Exxon well indicate that the sequence dips gently and overlies with distinct angular discordance the underlying steeply dipping volcanic rocks and intercalated sedimentary rocks, which have been dated on the basis of K-Ar analyses as being 16 to 20 m.y. old (middle Miocene) (Table 1, loc. 115); and (3) seismic data indicate that the clastic section predates the late Miocene block-faulting epsisode (13 to 12 m.y.).

Equivalents to this marine sequence appear to be the upper Miocene fluviolacustrine sedimentary deposits found in the central and eastern areas. The sequence may also be correlative with the redefined marine Split Mountain Formation (Woodward, 1974) present on the west side of Imperial Valley.

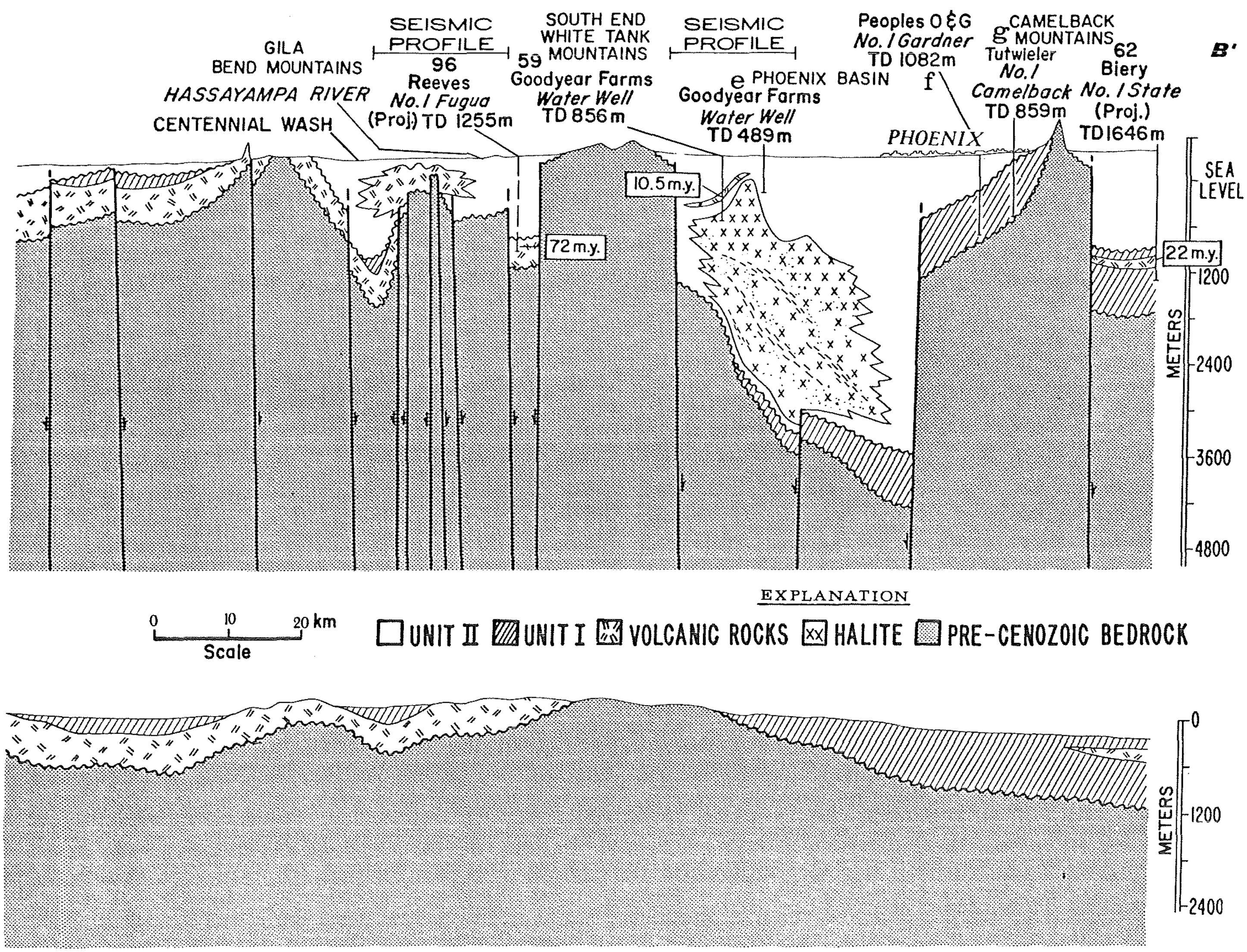

Figure 8. *(Continued).*

Marine Pliocene Bouse Formation. The Pliocene Bouse Formation in the Yuma basin (Metzger, 1968; Smith, 1970) unconformably overlies the previously described upper Miocene marine sedimentary strata. The Bouse Formation also overlies unconformably the upper Miocene fanglomerate in the Cibola-Parker area (Figs. 6, 10). In the lower Colorado River valley, this relatively flat-lying formation crops out at several localities north of Yuma and was penetrated in the subsurface near the international border by the Exxon Yuma Federal No. 1 well between 964 and 1,627 m.

In outcrops, the formation is composed of a basal white limestone overlain by an olive-gray claystone. Minor amounts of silt, sand, and gravel occur generally throughout the unit, and the silt and sand percentage increases upward. The basal limestone was not encountered by the Exxon well or by the Colorado Basin Associates, Inc. Federal No. 1 well, 10 km northeastward. At both locations, Bouse claystone rests directly on the older marine clastics already described. At the Exxon location the Bouse Formation is composed of fossiliferous light-gray claystone containing occasional thin beds of fine-grained light-gray sandstone with varying amounts of tuff. Occasional foraminifers, ostracods, charophytes, barnacles, and mollusks are contained in the formation, the mollusks being more common in the sandy upper part.

A tuff layer in the basal limestone of the Bouse Formation has been dated as 5.4 m.y. old (P. E. Damon, 1972, oral commun.; Table 1, loc. 122). This Pliocene date confirms that the Bouse is probably younger than the red-brown clays of the lower Gila River valley.

Possible Bouse Equivalents. Beds equivalent to the Bouse Formation have been recognized in several localities within the general area of this study. Noble (1931) described sedimentary strata similar to the Bouse along the Colorado River valley near Needles, California, and in the Chemehuevi Valley west of Lake Havasu (Fig. 1). Similar sedimentary rocks have also been observed as far north as Lake Mohave (Fig. 1), where Bouse-like white limy tuff and olive-green clays unconformably overlie a fanglomerate of local derivation in the washes east of the lake. Overlying the clays are Colorado River gravel deposits.

As a passing note, it has been suggested (Lucchitta, 1972) that the thick marine Imperial Formation cropping out in the mountains west of the Imperial Valley may correlate with the Bouse Formation. The only information collected during this study that may have a bearing on this problem was a stratigraphic relationship observed in the Coyote Mountains (Fig. 1, loc. 123) where the Imperial Formation seems to rest unconformably on the 16-m.y.-old Alverson Volcanics (Table 1, loc. 123).

STRUCTURAL DEVELOPMENT

Southwestern Arizona has a typical basin-and-range structure of mountain-forming horsts separated by valleys that are underlain by grabens or half-grabens. The prevailing structural grain trends in a northwest direction. Structural trends established prior to late Miocene block faulting normally are not recognizable. A notable exception is the Gila trough, which closely corresponds with the northeast-trending lower valley of the Gila River.

The following brief structural description of the area is almost exclusively restricted to the late Miocene block-faulting episode and associated beds of Unit II. Good seismic data allow interpretation, with reasonable certainty, of the attitude of these younger beds beneath the alluvium-covered valleys. Because the quality of seismic data below the unconformity is very poor, evidence relating to pre–late Miocene structuring is, on the other hand, restricted to the exposed remnants of Unit I in the mountain ranges.

The geologic structure of southwestern Arizona is illustrated by means of the five cross sections in Figures 7, 8, 9, 11, and 12. Their locations are shown on a generalized geologic map of the area (Fig. 3). On cross sections A–A′ and B–B′ (Figs. 7, 8), an attempt has been made to restore the topography and distribution of Unit I to the time just previous to the beginning of the deposition of Unit II. The cross sections are

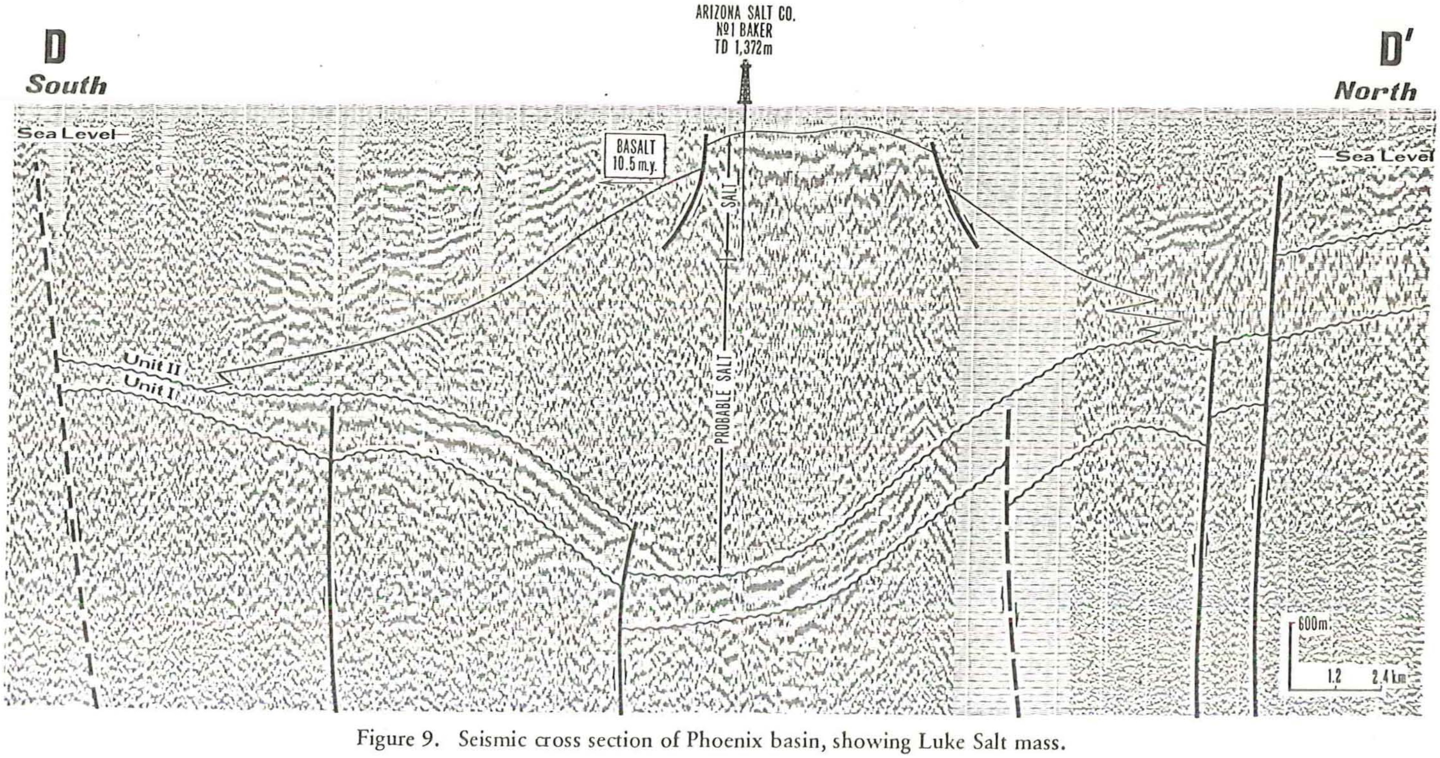

Figure 9. Seismic cross section of Phoenix basin, showing Luke Salt mass.

based on subsurface information, on seismic data recorded in the valleys, and on surface observations in the surrounding mountains.

Upper Tertiary Northwest-Trending Troughs

Section A–A′ (Fig. 7) crosses five depositional basins that border the central Arizona mountainous region. They are referred to on the cross section as the Phoenix, Chandler, Picacho, Redrock, and Tucson basins. They are the deepest fault trenches encountered in the study east of the Salton trough. As interpreted from seismic data and the lithology of the deposits that fill them, these fault troughs resulted from late Miocene block faulting. At shallow depths, all five troughs are simple structural basins, but with increasing depth they grade into narrow, complex grabens bounded by parallel to sharply converging normal faults. The grabens are irregular in shape but tend to be rectangular, having lengths about three to six times their widths. In a general way, they parallel the bordering mountain ranges.

Deep central parts of the troughs apparently are not interconnected. Depositional continuity seems to occur only at shallow depths in younger beds that extend laterally without interruption over and around buried horst blocks. As described in the section on stratigraphy, some basins contain thick sequences of evaporites. These evaporites are strong evidence that the northwest-trending troughs interrupted the regional drainage for a prolonged period of time, creating widespread lakes.

Section B–B′ (Fig. 8) crosses three depositional areas of special interest: the Yuma basin, the Gila trough, and the Phoenix basin. The Yuma basin is a segment of the eastern flank of the Salton trough and may be more closely related to Salton trough tectonics than to those of the Basin and Range province to the east. Presence in the Yuma basin of a thin Unit I is interpreted as evidence that this was a fairly stable area before the beginning of late Miocene block faulting and that most deposition occurred after this event. The basin is in trend with the San Andreas and Algodones fault zones and may have been modified by their movements.

Section C–C′ (Fig. 11) is a cross section of the Tucson basin, roughly at right angles to cross section A–A′, showing the structural relationship of this trough to the adjacent mountain ranges. The Tucson basin is one of five anomalously deep troughs and has structural characteristics typical of other troughs in the study area. Structure beneath the wide valley floor is composed of a narrow central graben between broad, sloping mountain pediments. The profile suggests that a once-narrow valley between broad ranges has grown in width at the expense of the eroding surrounding highlands.

Section D–D′ (Fig. 9) is a seismic profile across the Phoenix basin showing its block-fault structure and an interpretation of the shape and distribution of the Luke Salt mass. As described in the section on stratigraphy, subsurface well and seismic data show that upward movement of salt has domed the overlying sedimentary strata at the location of the Arizona Salt Company well.

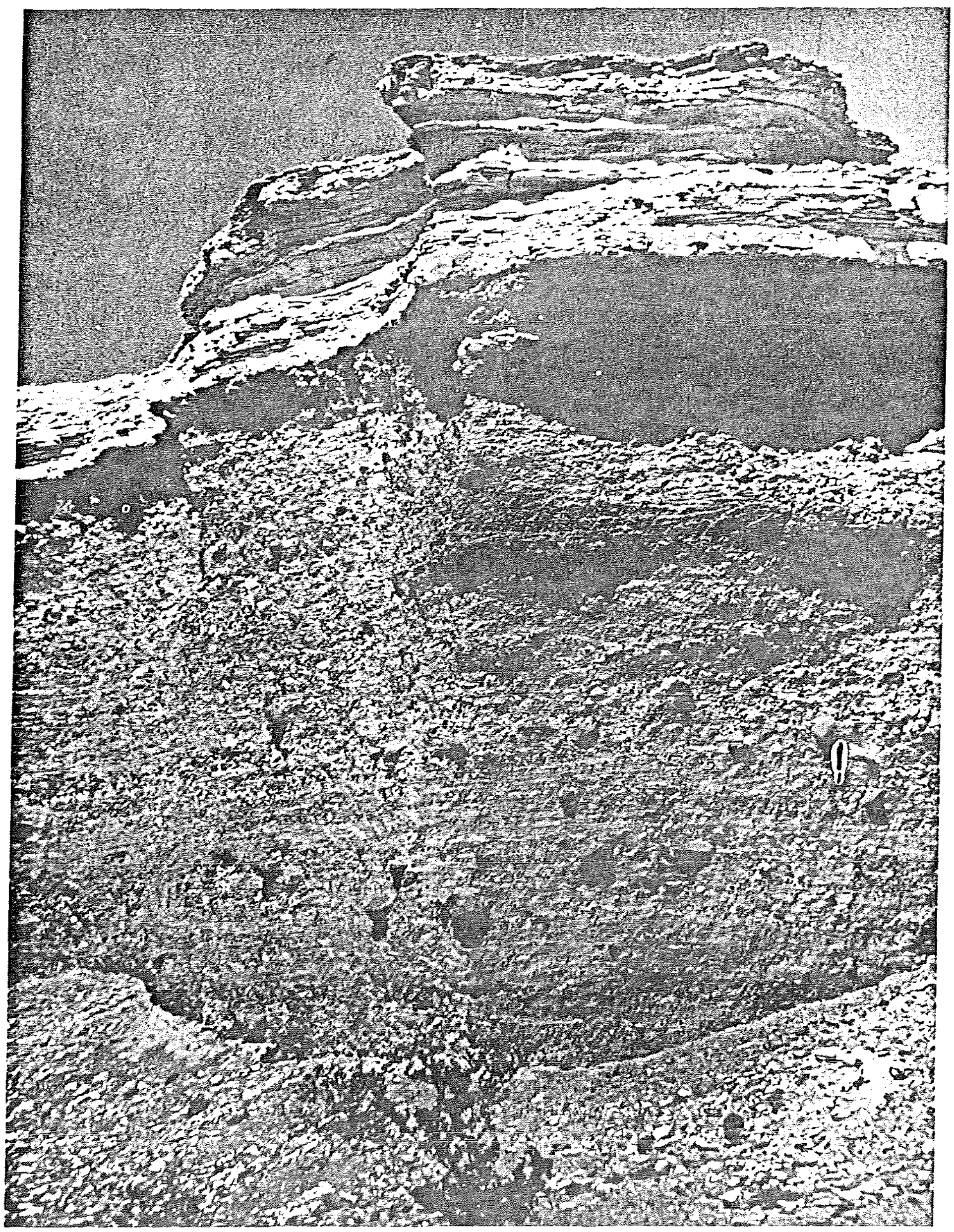

Figure 10. White Bouse limestone resting on middle Miocene fanglomerate near Cibola. Contact represents erosional surface.

Gila Trough

The Gila trough is a northeast-trending, sediment-filled trench underlying the lower Gila River valley east of Ligurta (Fig. 3). Thick deposits of Unit I in the trough indicate that it predated late Miocene block faulting. This block faulting overprinted the older northeast-southwest structural trend, forming horsts and grabens within the Gila trough that are aligned with the northwest-southeast trend of other present-day valleys and ranges.

The trough is 140 to 150 km long and 15

to 25 km wide. Section B–B′ (Fig. 8) follows roughly the axis of this trough for about 100 km between Ligurta and a point near Hyder where the line of section leaves the trough. Near Horn, the only place where Exxon seismic lines cross it at right angles, the Gila trough is a true graben bounded by two (or more) faults (section E–E′, Fig. 12). The trough was crossed by seismic lines at three other widely separated places, but the lines intersected its axis at low angles, making the interpretation of the geometry of the trough difficult. Seismic data indicate zones of abrupt stratigraphic thickening and faulting within the trough, but the orientation of these faults could not be determined with certainty. It seems probable, however, that the trough throughout its length is a graben or half-graben.

Sufficient data are not available to adequately explain the anomalous northeastern trend of the Gila trough. It may represent a reactivated Precambrian structural element, which controls the course of the lower Gila River and possibly even parts of the course of the Salt River upstream from Tempe.

GEOLOGIC HISTORY

Based principally on K-Ar age determinations of volcanic rocks and their stratigraphic relationships to associated sediments, the following is an attempt to reconstruct the chronology of geologic events in southwestern Arizona.

Beginning with the decline of the Laramide orogeny, about 53 m.y. ago and lasting until about 28 to 26 m.y. ago, southwestern Arizona was an area of general magmatic quiescence (Damon, 1966).

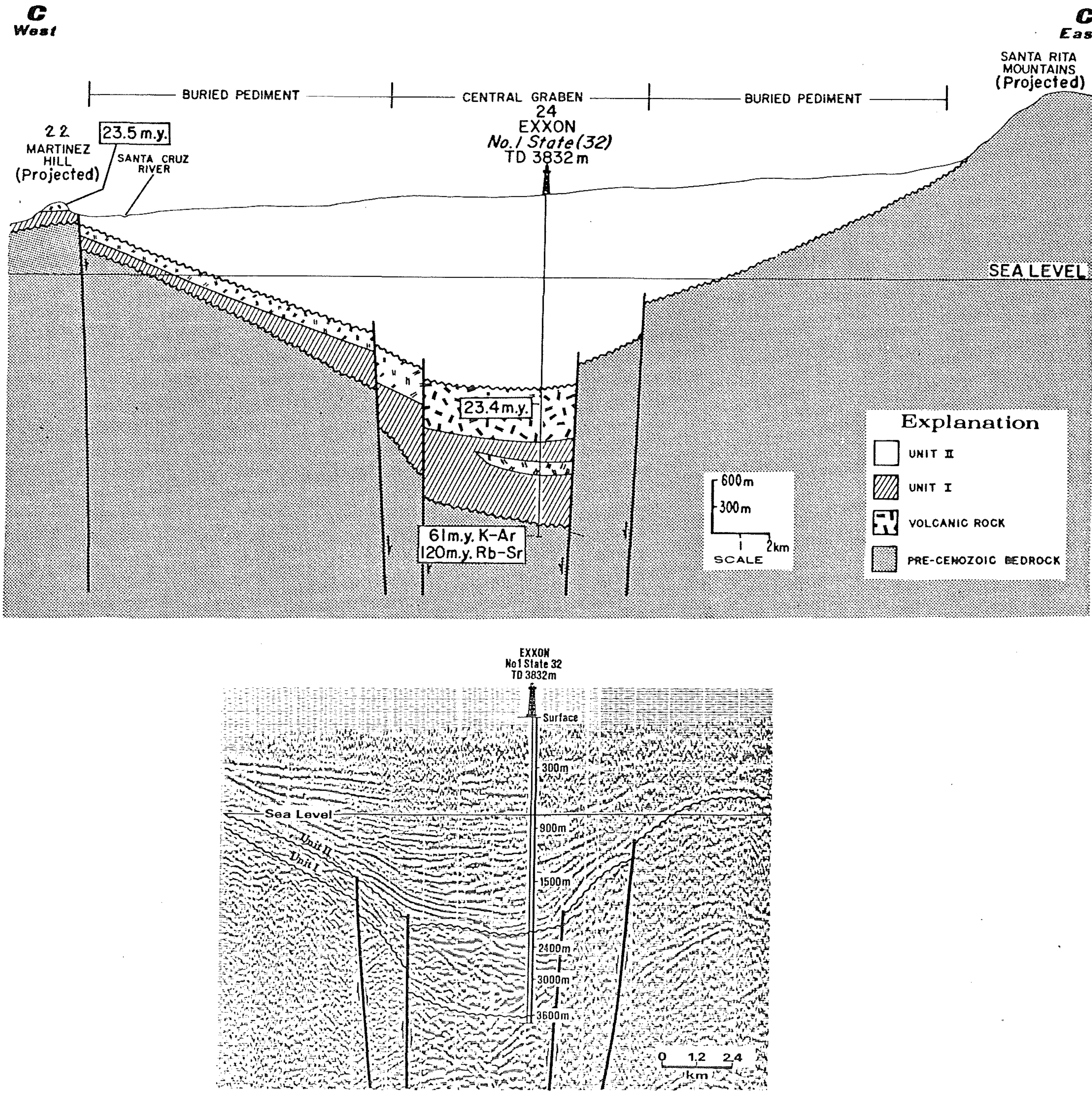

Figure 11. Structural cross section of Tucson basin (numbers refer to localities in Fig. 3).

This was a time when subaerial fanglomerates and associated lake beds were deposited in interior-drainage basins developed on older bedrock surfaces. The predominant red to reddish-brown color of the sedimentary strata indicates deposition in an oxidizing environment.

Widespread tectonism began approximately 28 to 26 m.y. ago, in late Oligocene time, and continued until around 20 to 17 m.y. ago (locally slightly later). This episode, known as the mid-Tertiary orogeny, was accompanied by regional heating of the crust, plutonism, minor mineralization, and extrusion of great quantities of rhyolitic to andesitic tuffs, breccias, and flows, which modified earlier drainage patterns and the location of depositional sites. Isolated lacustrine sediments were deposited in newly formed interior-drainage basins. Locally, torrential deposits of fluviatile red sandstone and boulder beds were intercalated with the volcanic rocks. Rocks deposited during and preceding this event were faulted, steeply tilted, and locally folded. Damon (1966) stated that large sections of the crust in the Basin and Range province were heated to high temperatures during the mid-Tertiary orogeny and that recrystallization of the Precambrian Catalina Gneiss north of Tucson occurred 28 to 26 m.y. ago. A quartz-diorite gneiss apparently having a similar history was encountered at 3,101 m in Exxon's State (74)-1 well near Picacho (Table 1, loc. 5). A K-Ar age determination of biotite separated from a core of this material yielded an early Miocene age of 25 m.y., whereas a Rb-Sr whole-rock determination on the same sample indicated a Precambrian age of from 1,275 to 1,540 m.y. These discordant ages lend additional support to Damon's conclusions.

"Thrusting" associated with the mid-Tertiary orogeny has been described near Parker and Tucson (Lasky and Webber, 1949; Wilson and Moore, 1959; Cooper, 1960). Lasky and Webber interpreted the presence of large exotic rock masses, brecciated blocks, and breccia beds of Precambrian and Paleozoic rocks in the Rawhide and Artillery Mountain areas as evidence of a "thrust sheet" within the Artillery Formation. In the Artillery Mountains, these large Precambrian and Paleozoic rock masses occur stratigraphically above the basalt member in the upper part of the Artillery Formation, which yielded a K-Ar age of 21 m.y. (Table 1, loc. 85). Field observations in this area, and others to the west in the vicinity of Parker, lead us to believe that this chaotic material does not represent remnants of thrust sheets but, rather, is gravity-induced landslide blocks and debris associated with wrench faulting. Similar gravity-induced rock masses have been interpreted in the Tucson area. Cooper (1960) described mudflow-landslide breccia and large individual block landslides in the Pantano Formation. Davidson (1970) hypothesized that some of the large outcrops of Precambrian and Mesozoic rocks in the western foothills of the Rincon and Santa Catalina Mountains east of Tucson are large landslide masses emplaced during deposition of the Pantano Formation. Davis (1975), however, suggested that these large outcrops of Precambrian and Mesozoic rocks represent gravity-induced folded remnants off of the Catalina-Rincon complex during domal uplift by ascent of gneissic domes and arches 28 to 24 m.y. ago. His data indicate that the gravity-induced folding during low-angle displacement took place under substantial cover, possibly 3 to 4 km. He did not present any evidence that wrench faulting was associated with the domal uplift.

With the waning of the mid-Tertiary orogeny, 20 to 17 m.y. ago, a profound unconformity surface was developed. Topographic lows became sites for fanglomerate and lacustrine deposition. Tuff beds and extrusive flows intercalated in the fanglomerates and lacustrine sedimentary strata indi-

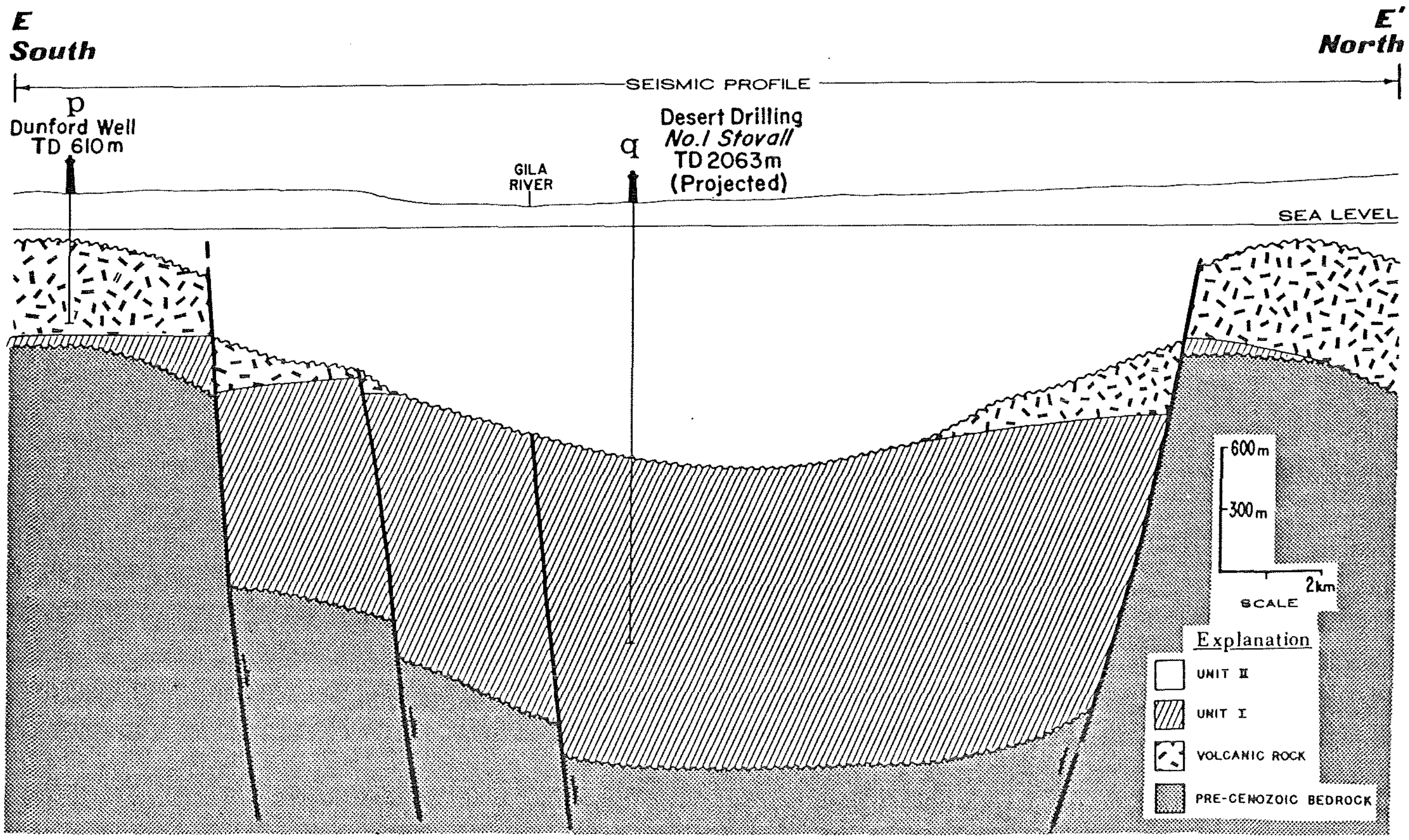

Figure 12. Structural cross section across Gila trough (letters refer to localities in Fig. 3). Seismic control shown above cross section.

cate continued volcanic activity. Subsequent faulting caused only minor tilting of these strata (Damon and others, 1973).

Regional block faulting began in late Miocene time, approximately 13 to 12 m.y. ago, and modified all earlier landforms. The preceding surface was converted into a horst-and-graben terrain, with the subsiding fault troughs forming new interior-drainage basins. These basins were depositional sites for locally derived detritus, and at least two basins in the study area contain thick bodies of evaporites. Peirce (1974) postulated that the thick evaporite sections found in the subsurface of some valleys between Lake Mead and the Picacho Basin were formed in deep troughs adjacent to the Colorado Plateau; he further suggested that these evaporites may all have had similar geologic histories. Sometime between 10.5 and 6.0 m.y. ago, probably nearer to 10.5 m.y. ago, faulting began to wane and sedimentation in previously separate interior basins began to coalesce. Anderson and others (1972) concluded that large-scale fault displacements in the Lake Mead area (Fig. 1) ceased before deposition of the Fortification Basalt. This member of the Muddy Creek Formation has K-Ar ages as old as 11.3 m.y.

Exterior-drainage systems began developing sometime between 10.5 and 6.0 m.y. ago. In the Phoenix basin a thin basalt flow occurring within lacustrine sediments and overlying the Luke Salt mass indicates that a closed basin environment was still present approximately 10.5 m.y. ago (Fig. 3, loc. 59). Presence of minor amounts of river gravels below 6.0-m.y.-old basalt near Gillespie Dam (Fig. 3, loc. 97) indicates that exterior drainage for the Gila River system began to form in early Pliocene time. Thick deposits of Gila River gravels below the 3.0-m.y.-old Sentinel basalt (Fig. 3, loc. 106) are evidence that throughgoing drainage was well established by late Pliocene time and probably reached the Yuma area.

The Colorado River entered the Parker-Cibola area sometime after deposition of the Bouse Formation (Metzger, 1968). According to Lucchitta (1972), the lower Colorado River drainage was developed between 10 and 3.3 m.y. ago, but probably after 5.4 m.y. ago.

High, flat-lying terrace deposits of the Colorado River, from the Grand Canyon to the Gulf of California, first noted by Lee (1908), are believed to be older than 3.0 m.y. Ross (1923) recognized old Gila River terraces some 20 to 25 m above the present lower Gila River flood plain. Horse bones found in these terrace deposits near Ligurta suggest an early Pleistocene age (Bryan, 1925). Lee (1905) described similar terraces 7 to 8 m above the Salt River at Mesa.

Available evidence suggests that volcanic activity increased in the central area with outpouring of basaltic lavas during the period from 6 to 3 m.y. ago (Table 1, locs. 97 and 106; Damon, 1971).

By 3.0 m.y. ago, the lower Gila River had reached its base level of deposition when the basalt flows around Sentinel were extruded on the surface. Since 3 m.y. ago, upwarping and eustatic changes of sea level have increased the gradient along the Colorado and Gila Rivers, allowing these river systems to remove great quantities of material from their lower valleys, thus exposing older valley-fill material in the adjacent bluffs.

Geophoto analysis of the study area shows only one minor remaining closed drainage basin. It is located southeast of the town of Sentinel, contiguous to the Sentinel basalt flows, and was probably formed when these flows disrupted local drainage.

ACKNOWLEDGMENTS

We gratefully acknowledge the help of many earth scientists in Arizona who willingly shared their knowledge of the area. We are indebted to members of the Laboratory of Isotope Geochemistry, Department of Geoscience, University of Arizona, for many radiometric ages and for prompt dating of samples from two of Exxon's wells. Their work was supported in part by National Science Foundation Grant EAR-76-02590 and the State of Arizona. We also thank the Arizona Bureau of Mines, the Arizona Oil and Gas Conservation Commission, the U.S. Geological Survey, and the Bureau of Reclamation for many favors. Finally, we acknowledge many other Exxon geologists and geophysicists who contributed to the interpretations presented here. H. W. Peirce read an earlier version of this manuscript and suggested changes for its improvement.

APPENDIX 1. SAMPLE DESCRIPTIONS OF EXXON'S STRATIGRAPHIC TESTS

Exxon State (74)-1 Well, Sec. 2, T. 8 S., R. 8 E., Pinal County, Arizona

Unit II

Depth 0 to 110 m: gravel, coarse, unconsolidated.

Depth 110 to 198 m: sand, unconsolidated; occasional gravel lenses; few clay stringers, red-brown.

Depth 198 to 707 m: clay, red-brown; occasional silty lenses, gypsum and anhydrite nodules and stringers in basal 230 m; sandy and silty from 595 to 655 m.

Depth 707 to 2,522 m: mostly anhydrite; occasional claystone stringer, green and greenish-gray; few thin tuff beds, green, bentonitic; scattered limestone nodules; few thin salt beds in upper part.

Depth 2,522 to 2,560 m: sand, reddish-brown, conglomeratic; claystone stringers, vari-colored.

Depth 2,560 to 2,765 m: conglomerate, reddish-stained, poorly consolidated; chiefly composed of volcanic fragments, purplish-red.

Middle Unit I
(Predominantly Volcanic Rocks)

Depth 2,765 to 2,946 m: basalt, purplish-red. Selected cuttings from 2,792 to 2,807 m yielded middle Miocene age of 17 m.y. Shafiqullah and others (1976) analyzed extrusion to be an ultrapotassic trachyte. Average age of 14.9 m.y. was obtained from 2,823 to 2,924 m for selected cuttings (Table 1, loc. 5).

Lower Unit I

Depth 2,946 to 3,001 m: conglomerate, reddish-stained, consolidated, chiefly composed of quartz-diorite gneiss fragments in matrix of sandstone and siltstone, dark red-brown, clayey.

"Pre-Eocene Bedrock"

Depth 3,001 to 3,102 m: (total depth): quartz-diorite gneiss, greenish-gray, highly fractured. Biotite separate of core samples from 3,101 to 3,102 m yielded K-Ar age of 25 m.y., whereas Rb-Sr whole-rock determination indicated Precambrian age of from 1,275 to 1,540 m.y. (Table 1, loc. 5). Reduced K-Ar age probably represents recrystallization of the gneiss during mid-Tertiary orogeny.

Exxon State (14)-1 Well, Sec. 25, T. 3 S., R. 11 W., Yuma County, Arizona

Unit II

Depth 0 to 155 m: gravel, unconsolidated.

Middle Unit I
(Predominantly Volcanic Rocks)

Depth 155 to 707 m: andesite, red and reddish-brown, basaltic; numerous zones of crystalline tuff. Selected cuttings of andesite from 229 to 238 m yielded K-Ar age of 20.5 ± 1.0 m.y. (Table 1, loc. 103).

"Pre-Eocene Bedrock"

Depth 707 to 777 m: granite, light colored, gneissic. Selected cuttings from 771 to 777 m yielded K-Ar age of 163.7 ± 4.0 m.y., whereas Rb-Sr whole-rock determination indicated Precambrian age of 1,080 m.y. (Table 1, loc. 103). Reduced K-Ar age probably represents recrystallization of the granite during Jurassic time.

Volcanic Intrusion?

Depth 777 to 808 m: (total depth): volcanic rock, greenish-gray, aphanitic; becomes reddish brown and purplish gray downward; highly brecciated and veined with calcite. Core sample at 799 m yielded K-Ar age of 21.3 ± 0.9 m.y. (Table 1, loc. 103). Interpreted to be a fissure dike.

Exxon State (32)-1 Well, Sec. 5, T. 16 S., R. 15 E., Pima County, Arizona

Unit II

Depth 0 to 259 m: sand and gravel, unconsolidated; some clay and siltstone in basal 60 m, red-brown.
Depth 259 to 350 m: sand, unconsolidated; clay stringers, red-brown.
Depth 350 to 813 m: clay, red-brown; abundant gypsum crystals between 564 and 686 m.
Depth 813 to 914 m: sand; some gravel lenses; numerous clay interbeds, red-brown.
Depth 914 to 1,170 m: sand, conglomeratic in basal 20 m.
Depth 1,170 to 2,218 m: sand, silt, and clay interbeds, red-brown; occasional conglomerate zone; anhydrite bed from 2,164 to 2,167 m.

Middle Unit I
(Predominantly Volcanic Rocks)

Depth 2,218 to 2,588 m: tuff, varicolored, basaltic andesite; numerous intercalated beds of sandstone and shale, red-brown and gray; shale contains anhydrite and gypsum blebs. Selected cuttings of tuff from 2,420 to 2,426 m yielded K-Ar age of 23.4 ± 0.6 m.y. (Table 1, loc. 24).
Depth 2,588 to 2,745 m: tuff, purplish-gray, rhyolite.

Lower Unit I

Depth 2,745 to 2,895 m: conglomerate, reddish-brown, consolidated; chiefly composed of volcanic, limestone, and chert fragments; occasional shale stringer. Volcanic material probably derived from pre-Eocene volcanic surface in Tucson area.

Volcanic Intrusion?

Depth 2,895 to 3,050 m: andesite, varicolored, basaltic, porphyritic. Selected cuttings from 2,895 to 2,898 m and 2,972 to 3,002 m yielded K-Ar ages of 16.1 ± 0.6 m.y. and 18.0 ± 2.0 m.y., respectively (Table 1, loc. 24). Interpreted to be an intrusive dike or sill.

Lower Unit I

Depth 3,050 to 3,525 m: conglomerate, reddish-brown, somewhat silicified; similar to conglomerate from 2,745 to 2,895 m; lower part sandy and contains beds of reddish-brown and gray silty shale.
Depth 3,525 to 3,660 m: shale, gray, silty, waxy.

"Pre-Eocene bedrock"

Depth 3,660 to 3,837 m: (total depth): quartz monzonite. Selected cuttings at 3,753 m yielded corrected K-Ar age of 61 m.y., whereas Rb-Sr whole-rock determination indicated earlier age of 120 ± 60 m.y. (Table 1, loc. 24). K-Ar date is a reduced age (see Table 1, locs. 28 and 31).

Exxon Yuma-Federal No. 1 Well, Sec. 8, T. 11 S., R. 24 W., Yuma County, Arizona

Unit II

Depth 0 to 964 m: Colorado River gravels.

Bouse Formation

Depth 964 to 1,247 m: gravel, sand, silt, and clay transition zone; contains large fragments of mollusks.
Depth 1,247 to 1,627 m: claystone, light gray; occasional foraminifer and ostracod.

Marine Upper Miocene Sequence

Depth 1,627 to 2,115 m: mudstones, light gray, greenish-gray, salmon colored; numerous foraminifer, scattered pelecypod fragments and echinoid spines; lower part contains beds of sandstone, light gray, fine grained, tuffaceous; in basal 40 m, sediment grades downward into sandstone, medium to course grained, conglomeratic.

Middle Unit I
(Predominantly Volcanic Rocks)

Depth 2,115 to 2,570 m: tuff, gray and reddish-brown, andesite; intercalated beds of sandstone and claystone, gray and reddish brown, tuffaceous, and clay, pale greenish-gray, bentonitic. Selected cuttings of tuff from 2,194 to 2,224 m yielded K-Ar age of 16 m.y. (Table 1, loc. 115).
Depth 2,570 to 2,743 m: andesite, varicolored, basaltic; intercalated beds of clastics ranging from shale to conglomerate, dark red to reddish brown, indurated, poorly sorted, dirty appearance.

Lower Unit I

Depth 2,743 to 3,286 m: granite wash; consists of subangular to subrounded gneissic and granitic rock fragments in reddish-brown silty matrix. Intervals from 2,767 to 2,804 m, 2,938 to 2,974 m, and 3,040 to 3,152 m consist of basalt, purplish-gray, andesitic, somewhat porphyritic. Selected cuttings of basalt from 3,078 to 3,108 m yielded K-Ar age of 20 m.y. (Table 1, loc. 115). These basalts are interpreted to represent an intrusive dike and sill system into prevolcanic section of Lower Unit I. Volcanic fragments are absent in intervening clastic beds.
Depth 3,286 to 3,488 m: (total depth): shale, dark red to reddish brown, silty, sandy, and sandstone, red, arkosic. Two basalts similar to those within interval 2,743 to 3,286 m occur from 3,310 to 3,342 m and 3,467 to 3,488 m.

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